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Damage Cost Models for Pollution Effects on Material

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DAMAGE COST MODELS FOR POLLUTION EFFECTS ON MATERIAL

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Two economic benefit models were developed to quantify the effects of ambient air pollutants on manmade materials exposed in urban environments. The models use existing physical damage functions, estimates of material in place and average repair or replacement costs to calculate the use life maintenance costs as a function of air pollutant concentration.

The first model, called the "prevailing practice model", assumes that existing maintenance practices represent a rational response to current levels of pollution and material properties. Information on the frequency of maintenance actions and the rate of damage predicted by existing physical damage functions is used to derive a "critical damage level". This critical damage level, defined as the amount of damage that is usually accepted before remedial action is taken, is assumed to be constant. The change in the rate of damage with changes in pollutant concentration can then be used to calculate a change in maintenance schedule, which, in turn, is converted to a change in maintenance costs over the use life of the material system under study.

The second model, called the "least cost model" does not make any assumptions about the appropriateness of current maintenance practices. Instead, the critical damage levels and maintenance criteria are directly specified by the user. The model then calculates the system use life costs for maintenance schedules based on these criteria for different pollution levels.

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ABSTRACT

Using estimates of material in place and existing pollutant/material damage functions gathered from the literature, damage cost models were developed to assess the effects of pollution on materials exposed in an urban environment. The pollutants and materials of interest were sulfur dioxide and metal, sulfur dioxide and paint, ozone and rubber, and total suspended particulate matter (soiling) and building surfaces (including windows).

The urban metropolitan area of Boston, Massachusetts was chosen as the study site. Two damage cost models were derived. The first model, entitled the "prevailing practice model", is based on existing maintenance practices. This model assumes that prevailing maintenance practices represent a rational response to current pollution levels. A survey of material users was performed to determine the existing maintenance/no maintenance practices as well as associated costs. The second model, entitled the "least cost model," uses mathematical pollutant/material damage functions in conjunction with specified action/no action decision points corresponding to degrees of material damage to predict the damage costs associated with changing levels of pollution. A simple annualized cost approach is used in the prevailing practice model while in the least cost model a net present value (NPV) approach is used to predict the lowest maintenance or replacement cost strategy.

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SECTION 1

INTRODUCTION

The damaging effects of air pollution on manmade materials have long been recognized. Over the last 50 years, a considerable amount of knowledge has been accumulated on the nature and extent of damage to materials by air pollutants. In this country a number of economic estimates of the cost of this damage have been made based on this knowledge, but there is little confidence in the estimates within the scientific community because of the lack of appropriate data and the crude estimating techniques used. The importance of accuracy in making damage assessments for cost-benefit determinations and a consideration of secondary air quality standards is obvious. The effects of material damage are part of the reason for the development of secondary air quality standards which are intended to protect human welfare (as opposed to human health).

The damage costs due to an air pollutant must be calculated in light of natural limits to the useful life of the material affected and options for repair, replacement or substitution. The incremental cost, that is, the cost associated with damage above that expected from normal wear or use in an unpolluted ("clean") environment, is the most important factor in the consideration of the costs and benefits of pollution control. More specifically, the damage to a given material by a single pollutant must be assessed if the benefit to be gained by reducing that pollutant is to be calculated.

Accurate estimates of the costs of air pollution damage to materials, the disbenefit (conversely, the benefits of avoiding such damage), are difficult to achieve. Such estimates must not only take into account many important physical and chemical interactions, but must also consider socioeconomic factors. Aesthetic judgment, an awareness of alternatives, and the cost of capital are only a few of the factors which can strongly influence incurred costs.

In order to determine the costs associated with the exposure of materials to ambient pollutant levels, several types of information are necessary.

1. The distribution and exposure of the materials of interest.
2. The rate at which damage is incurred under actual exposure conditions.
3. The amount of damage which necessitates remedial or preventive action (critical damage level).
4. The type and cost of remedial or preventive action actually taken.

Models for assessing the distribution and exposure of exterior materials are available but are still unproved in general application. Recent studies performed for the Environmental Protection Agency (EPA) (Koontz, 1981) and the Electric Power Research Institute (EPRI) (Stankunas 1983) have made a positive attempt to quantify the amounts of materials in place in urban environments. Although both studies are limited to assessments of conditions typical of the eastern United States, both studies serve as a useful starting point in determining the dis- tribution of materials.

Studies of the relationships between pollutant exposure and materials damage have taken two basic forms:

- Comparative damage of samples exposed to two or more different environmental regimes for extensive periods of time.
- Exposure of samples to synthetic environments under laboratory conditions for accelerated testing.

These methodologies in one way or another provide the basis for damage functions that relate physical damage to pollutant concentrations and other environmental factors. In spite of the lack of specificity in field studies, and the questionable representation of real life situations by laboratory studies, it is generally believed that reasonably accurate damage functions exist for zinc and certain types of paints in the presence of sulfur dioxide (SO_2) and humidity.

Little information is available on the thresholds of damage which lead to remedial or preventive measures. Information on "normal" practice is particularly lacking except for comments on the frequency of repair or gross estimates made on the basis of sales of materials compared to arbitrary "lifetimes" of the structures in question. The issue is further complicated by the range of possible strategies for dealing with damage and the options available to implement those strategies.

The only area where reasonable, accurate information is readily available is in the area of costs once a maintenance action is defined. Bids for various maintenance or substitution practices are available from many sources.

The objective of this report is to present a relatively simple method for estimating the damage cost of air pollution with regard to its effects on non-living materials, and to establish a framework by which the estimates maybe improved when additional information becomes available.

Damage costs differ from a true benefit cost, in that the calculation of damage costs for air pollutant incorporates the estimation of physical effects and a prediction of producer or consumer response. The definition of benefits for air pollution effects includes both the estimation of effects, prediction of response, and also, the analysis of market structure and supply and demand. In the case of air pollutants, the slope of the demand curve and changes in response may be small enough to approximate a true benefit using the damage cost.

Two methods for estimating the damage cost of air pollution are developed and applied. The first method is a simple approach in which current maintenance practices determined from field surveys are extrapolated into general rules or functions. These rules or functions are then applied in hypothetical situations where factors such as the pollutant level vary slightly and the resulting change in maintenance and replacement costs is calculated. The second method is a more complex model which uses available pollutant damage functions and specific critical damage levels to calculate damage costs directly. The complex model is somewhat more theoretical but it allows consideration of various alternative maintenance strategies such as painting (versus not painting) and other conditions such as changes in the interest rate which may be significantly different from those currently influencing actual practice. The complex model can thus be used to derive an estimate of costs for conditions or maintenance strategies not currently in use, including a theoretical ideal or least economic cost approach.

The basic concepts of damage cost models are discussed and a general framework for modeling presented in Section 4. The selection of materials and pollutants for study, selection of damage functions, and economic considerations are detailed in Section 5. This information is then applied to several specific problems: sulfur dioxide damage to metals, sulfur dioxide damage to painted surfaces, soiling by particulate matter and oxidant damage to elastomers. The results of these analyses are presented in Sections 6 through 9. The complex model, termed the least cost model, is presented in Section 10.

This work was performed under a research program entitled "Benefit Model for Pollution Effects on Material" for the Environmental Sciences Research Laboratory of the U.S. Environmental Protection Agency, at Research Triangle Park, North Carolina by TRC - Environmental Consultants, Inc. under contract number 68-02-3447.

SECTION 2

SUMMARY AND CONCLUSIONS

A damage cost model was developed to assess the damaging effects of ambient concentrations of air pollutants to manmade materials exposed in the urban Boston environment. Physical damage functions which quantify the rate of damage to exposed materials, the cost of repair or replacement to correct the damage, and estimates of the amount of susceptible material in place exposed in the urban environment were used as input to the damage cost model.

Pollutant/material combinations selected for study were sulfur dioxide and metals (steel and zinc), sulfur dioxide and paint, total suspended particulate matter and soiling, and ozone and elastomers.

Two damage cost models were developed. The first model is entitled the "prevailing practice model." In this model, current maintenance practices (prevailing practice) are considered to represent a rational response to current levels of pollution and uses of materials. From information on the frequency of maintenance and known physical damage functions, the critical damage level, defined as the amount of damage sustained before remedial action is taken, may be derived. Assuming that the critical damage level is constant, the time required to reach that level of damage at various levels of pollution may be derived. This change in maintenance schedule may then be converted to a change in maintenance costs over the lifetime of the material system under study.

Normal or prevailing maintenance practices for materials of interest were determined by conducting a survey within the Boston Metropolitan Area, defined as the area inside the inner beltway of Route 128.

The second model, entitled the "least cost model", is based on the physical damage functions, user-specified critical damage levels and selected maintenance/no maintenance decisions. These variables are used to calculate the least cost maintenance/replacement strategy for different ambient levels of air pollutants and material types or systems.

The principal difference between the two models is that the prevailing practice model takes the interval between maintenance operations as a given and uses it to estimate the corresponding typical critical damage level, whereas the least cost model allows the critical damage level to be set by the user and then calculates a maintenance schedule and associated costs. By allowing a broader range of maintenance strategy alternatives, the least cost model also allows the theoretical assessment of a strategy under conditions which differ significantly from those currently in force.

Estimates of bare galvanized steel and coated steel material exposed in the Boston Metropolitan Area and normal maintenance practices for the repair and replacement of these materials were obtained from surveys or empirical techniques. The maintenance practices reviewed include those for highway structures (bridges, signs, poles, guardrails), chain-link fencing, and electric transmission towers. One interesting result of the survey was that for the majority of galvanized materials, no preventive maintenance is routinely undertaken.

The amount of painted surface in the Boston Metropolitan Area was estimated based on the results of prior material-in-place surveys. The prevailing maintenance practice selected for paint, a 5-year repainting frequency, was based on a survey of residential house painting practices in the Boston area. Economic factors, however, such as income level, associated opportunity costs for households, and the value of a homeowner's labor have considerable impact on this frequency. Application of the 5-year maintenance frequency in conjunction with the existing mathematical damage function demonstrates that only a small portion of the damage costs to paint is attributable to SO_2, which may be a result of the form of damage function used. The existing damage functions for paint generally have variables for time of wetness and ambient pollutant level. However, these damage functions primarily address erosion of the painted surface, not the peeling and cracking of the surface most closely associated with the need for repainting in actual practice. A better damage function would incorporate other variables, either pollution or climate, to account for these failure mechanisms as well as erosion effects.

The evaluation of total suspended particulate matter (TSP) and soiling proved to be a difficult problem since available damage functions relating soiling to TSP are for a highly reflective white surface. The amount of white painted surfaces; the amount of dinginess acceptable on white and other color surfaces before maintenance is performed; and the amount of painting accomplished to address dinginess as compared with the normal wear and tear of a painted surface are unknown. The survey of normal practice indicates that washing surfaces on homes and buildings (apart from surface preparation prior to repainting) is done infrequently if at all. A survey of maintenance practices for window washing in the Boston area, which are expected to be directly proportional to TSP levels, shows that potential benefits or disbenefits would not be in the form of direct costs associated with actual changes in maintenance practices but that these benefits or disbenefits are in the form of cleaner windows and/or less visibility impairment at the same cost. More information is needed on actual maintenance responses to soiling on exterior surfaces as well as the development of better damage functions for soiling of other materials by particulate matter.

The relationship between ozone damage and rubber tires was analyzed and two areas of benefit or disbenefit were identified. Benefits or disbenefits accrue on both a regional and a national scale. On the regional scale, changes in ozone concentration would result in small benefits to the retread industry in the form of an increased number of available casings. On the national scale, changes on the manufacturing level occur as the amount of antiozonant added to tires can be adjusted. As national, as opposed to regional, ambient ozone levels decrease, less antiozonant needs to be added to each tire to provide the same level of protection currently afforded. This will result in lower costs at the manufacturing level, and ultimately at the consumer level. However the benefits associated with changes at either the national or regional level are relatively small.

In summary, the analysis of these four pollutant/material relationships shows:

- The damage functions for steel and zinc in the presence of SO_2 are well-defined. The costs attributable to SO_2 damage in the form of shortened use life and accelerated maintenance are relatively small based on the prevailing practice approach and the present net value approach.

- The present damage function for paint is not adequate to characterize damage definitively. Peeling and cracking of the painted surface are the primary forms of damage; these types of damage are not adequately treated in existing calculations. The equation lacks other climatic data such as heat, cold, sunlight, wind and temperature which have an impact on the use life of a painted surface. In addition, the damage function does not address the new types of coatings currently available in the marketplace. Normal practice is highly variable and external economic factors play an important part in the desire to repaint.

- The current damage function for ozone versus rubber appears to fit the existing data well. The costs associated with changes in ozone level within the market-place are very small.

- Available damage functions for soiling by TSP do not address the effects of soiling on the range of colored materials of interest. In addition, neither the critical damage level, the point at which action is taken, nor normal practice could be well-defined. Washing appears to be limited to special cases only, such as in preparation for repainting. Information is lacking on how much repainting is performed due to soiling and how much is due to failure of the painted surface.

SECTION 3

RECOMMENDATIONS

The results of the assessment of material damage due to atmospheric pollutants indicates several weaknesses in methodology. These are: uncertainties to the amounts of exposed material in place on a nationwide scale; the lack of knowledge of the response of the industrial and private sectors to the effects of air pollution; and the failure of several of the physical damage functions together to address the major factors leading to action. These weaknesses undermine the potential accuracy of economic estimates. To rectify this status, the following recommendations are made:

- Conduct a survey of normal or prevailing practice targeted to urban and rural settings throughout the country to see how the public and private sector respond to conditions prompting maintenance. Updated estimates of the actual cost of air pollution can be derived from this survey.

- Improve the estimation techniques for the exposure of susceptible materials in place on a national basis to incorporate different geographical and climatic conditions in the country. These factors would be used as primary input to the estimation of material damage nationwide.

- Improve the physical damage function for paint by incorporating climatic and other effects in addition to SO_2 and relative humidity parameters. The existing damage function is not adequate to assess the absolute change in paint depth or condition. The damage function must be corrected for different types of paints such as latex, oil and coil as well as different surfaces.

- The magnitude of the problem as well as public response to soiling must be better defined. Soiling appears to be a highly localized effect and the response to it is not well-defined. The existing damage functions are not adequate for any other materials or colors except white paint and white asbestos shingles.

- Consider the effects of the size and types of particulates as a factor which may influence the soiling function. EPA is currently funding a study to investigate these effects.

- The effects of wet and dry sulfate deposition in the form of acid rain and the fallout of sulfate particles may combine with SO_2 and degrade both paint and metal surfaces exposed outdoors. Additional studies of these effects are necessary to properly quantify their role in material damage.

Information gathered in these six areas will help to improve the accuracy and the reliability of estimating the potential benefits and costs due to changes in ambient concentrations of atmospheric pollutants.

SECTION 4

DAMAGE COST MODEL

GENERAL CONCEPTS

There are two fundamental approaches to estimating the economic impact of air pollutants on materials: the comparative approach and the analytical approach. The first is an empirical comparison of total expenditures and/or a loss of amenity due to material damage under different atmospheric pollutant conditions, followed by the development of quantitative relationships between cost and pollution. The analytical approach is based on the calculation of the physical damage from a given atmospheric pollutant concentration by means of physical damage functions and the quantification of the economic and aesthetic responses to that damage. The cost versus pollution relationships are derived from calculated effects.

Each approach has its advantages and disadvantages. The comparative approach is conceptually the simpler of the two, but is subject to uncertainty regarding its applicability. The greatest uncertainty in this approach arises in describing those comparative situations in which conditions, other than those on which cost/pollution relationships are based, differ. As an empirical approach it is also subject to error from factors such as covariance or the spurious correlation of variables.

The analytical approach theoretically is more widely applicable and its development may lead to fundamental insight into the nature of the problem.

However, the more complete the analysis desired, the more information is required, and much of the essential information is not currently available.

The models presented in this report are essentially analytical models. It is hoped that this type of analysis will not only provide a reasonably accurate method of estimating materials damage now, but will help to clearly define the type of information most urgently needed to improve estimates in the future.

In the analytical models, a number of key factors must be addressed:

- the amount of susceptible material exposed to pollution
- the degree of exposure (that is, the concentration of the pollutant)
- the relationship (damage function) which defines the amount and rate of damage due to pollutant/material interactions in a given environment
- the guidelines of when and what type of action is taken when damage occurs
- the total cost of damage over the lifetime of the system composed of the materials under study

The first step in the analysis is a definition of scope. In this step the pollutants and materials are defined, and the appropriate damage functions selected. It is essential to define the materials under study in terms of the system or application of which they are a part. Factors such as the exposure to ambient pollution levels, the amount of damage which is acceptable and the cost of the damage once it is incurred are all dependent on the use to which the material is put. For example, the zinc used in the galvanized steel in chain-link fencing has a distinctly different life history and pollutant exposure than the zinc used in an interior air conditioning duct.

The next step in the analysis is the calculation of accumulated physical damage to the material being studied. Physical damage is defined as any change in properties which decreases the utility of the system of which the material is a part. The concept of utility is not limited solely to functional attributes; it may also involve aesthetic factors.

Next is the assessment of the accumulated physical damage to the materials system in terms of general application. This application includes the definition of various critical damage levels which represent significant changes in either the current utility of the system or the rate at which additional damage will accumulate.

At each stage in the model a decision is made as to whether remedial action will be taken. In addition to the amount of physical damage, this decision relies on calculations which include such socioeconomic factors as the penalty costs of inaction, the opportunity costs of capital, the perceived loss of amenity, social and legal sanctions and the ability to pay. In actual decisionmaking (prevailing practice) much of this calculation is not specified, but is a function of the general consensus of what constitutes a proper approach. Prevailing practice is often the result of the experience gained through trial and error rather than through a formal calculation.

In any case, the next step in an analytical model is the calculation of costs which result from the decisions made in a strategy for use of a material. If simple replacement or repair is implemented, the direct costs are assessed and accumulated. If other actions were taken (including no action) the appropriate changes in material exposure and damage functions are made and the analysis is continued until the stated use life of the materials system is exhausted.

Aesthetic costs or uncompensated loss of amenity are not directly calculated. However, direct costs incurred for aesthetic reasons can be derived by comparing the difference between the total costs accumulated for scenarios where the strategy for use either includes or does not include critical damage points for aesthetic considerations.

In cases where the use life of the materials system is considered essentially infinite, the analysis is carried out for a time period long enough to reflect the equivalent annual cost of maintenance.

Two analytical models have been developed, a simple model and a complex model. The simple model, called the prevailing practice model, reflects current maintenance and replacement practices. It is assumed in this model that such prevailing practice is the result of well-informed decisions and represents the best possible approach.

The complex model, or least cost model, uses pollutant damage functions, current ambient pollutant concentrations, specific critical damage levels and a maintenance or replacement decision matrix to determine a least cost economic strategy independent of the prevailing practice.

PREVAILING PRACTICE MODEL

The prevailing practice model is based on several assumptions. It is assumed that the current strategies for the use of material systems incorporate decisions based on accurate information of both physical and socioeconomic factors. [This assumption may no longer be valid due to the rapid introduction of new materials and the relatively recent changes in ambient air quality which have drastically changed material/environment interactions. Strategies for use which are actually practiced may not yet reflect these changes since the consequences of the changes are not yet apparent. This lag between a change in conditions and a change in response may be partially reflected in the differences between the results of the simple model and the more complex approach. This comparison has not been done here.]

The simple model is still a useful tool, however, because it automatically includes a number of variables which are difficult, if not impossible, to define precisely. Several of these variables are socioeconomic as well as physical in nature, such as the level of damage which prompts repair and replacement. It is also a model which may be applied with reasonable accuracy and without extensive (and expensive) data gathering.

The simple model requires information on the lifetime of materials systems in the ambient environment. Lifetime is distinguished from the use life of the system as being the time of exposure experienced until a critical damage level is reached at which action is taken and/or real costs are incurred. Use life is defined as the time period over which the material system is expected or needed to be used. For example, a newspaper has a lifetime significantly longer than its typical use life. That is, it is usually discarded long before it has physically deteriorated to the point at which it can no longer be read. A painted house, on the other hand, has a use life far in excess of the lifetime of the paint. Accordingly, maintenance of the house paint is usually performed. A schematic outline of the prevailing practice model approach is presented in Figure 1.

Using currently practiced maintenance strategies, a lifetime for the material is determined. This lifetime could be the interval between applications of paint or the interval between replacement of steel

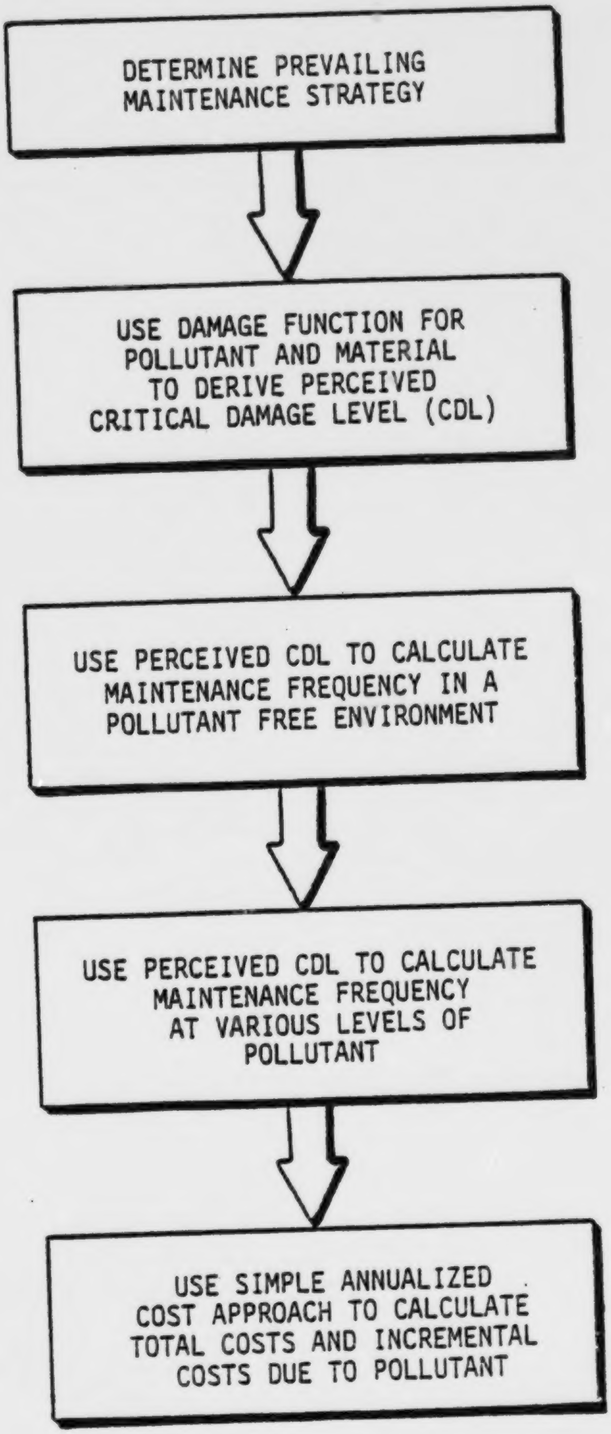
DETERMINE PREVAILING MAINTENANCE STRATEGY
USE DAMAGE FUNCTION FOR POLLUTANT AND MATERIAL TO DERIVE PERCEIVED CRITICAL DAMAGE LEVEL (CDL)
USE PERCEIVED CDL TO CALCULATE MAINTENANCE FREQUENCY IN A POLLUTANT FREE ENVIRONMENT
USE PERCEIVED CDL TO CALCULATE MAINTENANCE FREQUENCY AT VARIOUS LEVELS OF POLLUTANT
USE SIMPLE ANNUALIZED COST APPROACH TO CALCULATE TOTAL COSTS AND INCREMENTAL COSTS DUE TO POLLUTANT

Figure 1. Prevailing practice model.

fencing. A physical damage function, which relates the concentration of a given pollutant to physical damage, is selected. The pollutant level and other environmental factors are then used in the physical damage function to define a critical damage level, expressed in measurable damage units such as the depth of erosion or degree of corrosion, consistent with the prevailing lifetime of the material. This critical damage level is then used in conjunction with the damage function assuming a zero level of pollutant concentration to define lifetime in an unpolluted environment. Note that this step may not be necessary if accurate information on the clean air lifetime of the material is available from other sources.

The damage function and defined critical damage level are then applied with the projected pollutant levels of interest and a projected lifetime of the material is calculated. The calculated lifetimes are then used to determine the costs attributable to each pollutant level, and subsequently the benefit or disbenefit of the change in pollutant level from that currently experienced.

LEAST COST MODEL

The least cost model is much more complex than the prevailing practice model described above. Instead of simply accepting the typical period between maintenance activities as the lifetime of the material, this model is used to calculate the maintenance schedule most appropriate for minimizing total cost. These calculations are based on physical damage functions, externally derived critical damage levels, and information on economic factors such as the cost of capital (discount rate) as a function of income for various groups.

As in the simple prevailing practice model, the first step is to define the nature of the materials system and pollutant interactions of interest. However, unlike the simple model, the progressive changes in the rate at which both physical and economic damage accumulates as a function of previous history must be included. For example, if painted, galvanized steel fencing is the material system and SO_2 is the pollutant of interest, the rate at which physical damage to the paint, the zinc, and the steel accrues will depend not only on the ambient environment, but on the degree to which each of the materials has been exposed to that environment. As long as the painted surface is completely intact, with no eroded areas or pinholes, the rate of damage to the underlying zinc and steel is essentially zero. However, if after a period of exposure a portion of both the paint and the zinc surfaces are damaged, damage will begin to occur at the steel surface in addition to continuing damage to the paint and zinc. If undercutting of the zinc and paint occur, due to corrosion of the steel substrate, the rate at which they are damaged will increase as well.

The least cost practice model accounts for these changes by allowing the condition of the system to change as described by critical damage levels.

The rate of accumulation of economic damage is likewise a function of the critical damage levels since they are usually defined as either changes in the rate of accumulation of economic damage and/or changes in system utility.

In practice the critical damage levels are specified in the model. The appropriate physical damage functions are used to define the length of time required to reach each critical damage level for a given set of environmental conditions. A cost factor is associated with the maintenance performed within the period between changes in critical damage level. The model then calculates the use life costs for different maintenance schedules and adjusts the costs to account for the cost of capital. The least cost maintenance schedule is then determined, and the total cost noted.

The impact of a change in pollutant level is determined by the total minimized costs of maintenance at different levels of pollutant concentration.

The impact of changes in other factors, such as the acceptability of different levels of aesthetic damage, can be determined by requiring a maintenance schedule based on damage functions and critical damage levels for aesthetic effects. So instead of automatically minimizing the maintenance costs, the total costs are determined, at least in part, by the frequency of maintenance. (Note that the separation of aesthetic and functional damage is based on the assumption that the prime difference between actual costs and minimum costs is due to aesthetics. If the difference is also due, in part, to an ignorance of the alternatives or to outdated information, the portion of total cost subsequently assigned to aesthetics may be in error.)

A schematic diagram of the least cost practice model is illustrated in Figure 2.

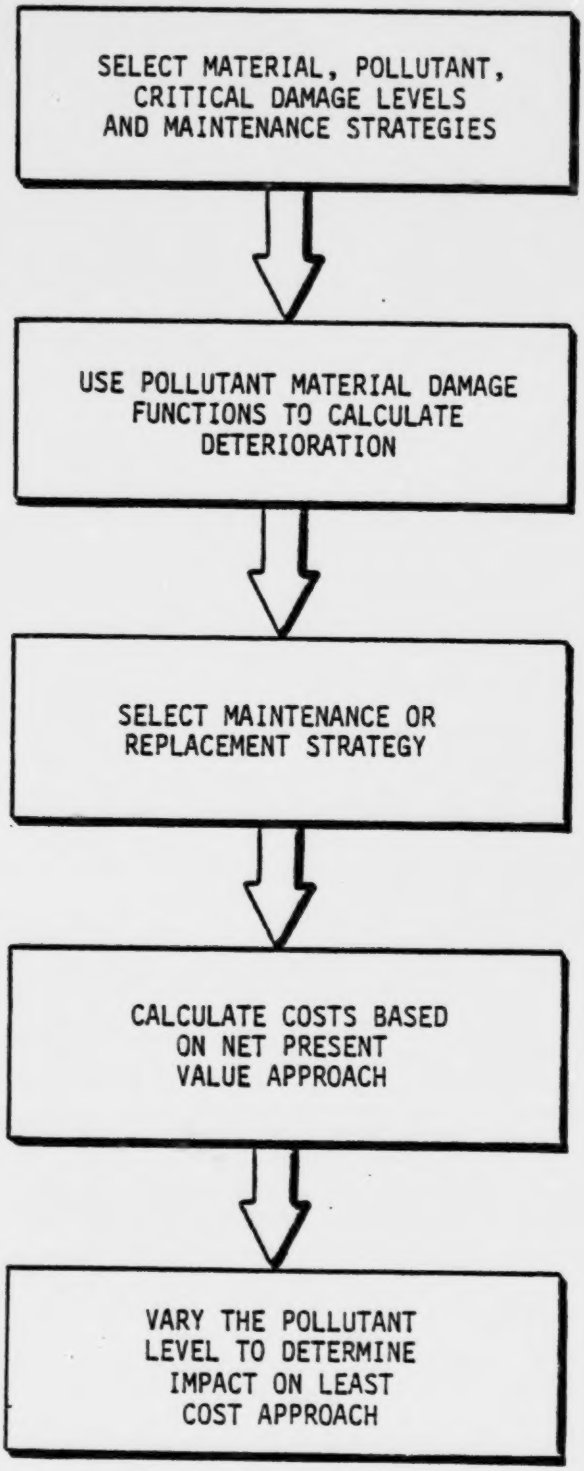
SELECT MATERIAL, POLLUTANT, CRITICAL DAMAGE LEVELS AND MAINTENANCE STRATEGIES
USE POLLUTANT MATERIAL DAMAGE FUNCTIONS TO CALCULATE DETERIORATION
SELECT MAINTENANCE OR REPLACEMENT STRATEGY
CALCULATE COSTS BASED ON NET PRESENT VALUE APPROACH
VARY THE POLLUTANT LEVEL TO DETERMINE IMPACT ON LEAST COST APPROACH

Figure 2. Least cost practice model.

SECTION 5

MODEL DEVELOPMENT

SELECTION OF MATERIALS

So many materials currently in use are exposed to pollution that it is not practical to attempt to quantify all damage costs due to every air pollutant. There are two basic approaches to limiting the number of combinations considered. A number of materials may be chosen for study on the basis of economic importance, and the list limited to those which are known to have significant damage reactions with common air pollutants. Conversely, a list of materials which are known to respond to air pollution exposure could be drawn up, and limited to those which are economically important. The key is that the final list should contain those materials for which pollution exposure has a serious economic impact. To warrant detailed study, a material should be both affected by a pollutant and be of economic importance.

An objective approach is taken to determine whether a certain material/pollutant combination must be studied. The criteria used in this analysis are:

- amount of susceptible materials in place
- cost of replacement
- penalty costs of delayed action
- air pollution perceived as a significant feature in the lifetime of the material

The amount of material exposed to pollution and susceptible to damage is the first consideration. It makes little sense to determine the cost of damage that sulfur dioxide (SO_2) does to buggy whips, even though leather is susceptible to such damage, since their economic importance is limited. Conversely, painted surfaces in the ambient environment represent both a large amount of exposed surface area as well as a material damaged by SO_2. The cost of replacement of the material as well as the penalty cost of delayed action must also be considered in selecting the material and pollutant combinations for study. Finally, the pollution must be thought of as a significant feature in the lifetime or use life of the material.

After a review of the literature on material damage due to air pollution, four pollutant/material combinations were selected for study:

- SO_2 - galvanized surfaces
- SO_2 - painted surfaces (including coated steels)
- O_3 - rubber products
- TSP - soiling of surfaces

Zinc is the only metal, used in sufficient quantities outdoors, that is exposed as a bare metal surface and directly affected by SO_2. Steel used outdoors will usually be coated (either painted or galvanized). Thus, even though bare steel is attacked by SO_2, bare steel is not used outdoors in significant quantities to have an impact on damage estimates. An exception to this is steel whose metallurgy is specially formulated to withstand normal weathering (for example, U.S. Steels' COR-10 steel). Copper and aluminum are widely used outdoors, however, aluminum is a fairly inert metal and is not susceptible to corrosion by SO_2; copper develops a protective coating which prevents further damage. The stress corrosion of aluminum has been identified as a potential problem but is not addressed in this report.

Of the paints used outdoors, oil-based and latex paints have been shown to be most susceptible to damage by SO_2. Vinyl coil coatings, acrylic coatings, and automotive finishes are relatively unaffected by SO_2.

Ozone can cause cracking in rubber products, therefore weakening the material and shortening its use life. Particulate matter causes the soiling of glass and wall surfaces which necessitates cleaning for aesthetic reasons.

POLLUTANT/MATERIAL INTERACTION

There is no question that the presence of air pollutants, notably sulfur oxides, particulate matter, nitrogen oxides and ozone under the proper circumstances can exacerbate damage to nonliving materials, resulting in economic expense for society.

There are several fundamental problems in quantifying the extent of damage to materials from specific pollutants:

- The types of damage associated with air pollutants also tend to occur in unpolluted atmospheres and cannot be unequivocally distinguished from that caused by other factors. Damage can be produced by moisture, CO_2, natural particulate matter, sunlight and other features of the natural environment. Thus, determining the isolated influence of a given pollutant in an ambient exposure situation is not a straightforward process.

- Laboratory studies where individual pollutants are introduced to sensitive materials independent of other influences tend to be conducted at unrealistically high concentrations and otherwise are not representative of actual exposure situations. These types of studies are designed to demonstrate cause and effect relationships. Attempts to extrapolate these results to ambient concentrations produce damage estimates of questionable value.

- Reduction in ambient levels of pollutants such as SO_2 as a result of air pollution control efforts has significantly reduced the exposure and degree of damage to materials. However, the switch from oil to coal could reverse this trend.

- Changes in types of materials and protective strategies resulting from technological improvements in materials have a fundamental effect upon the nature and extent of air pollution-induced damage to materials and associated damage costs.
- Determination of the quantities of materials in place in relation to air pollutant exposures is a difficult task, especially when significant amounts of certain materials (for example, fabrics, paints and paper) may be exposed to indoor environments or other locations not represented by typical ambient monitors.

In developing damage cost models, the first step is directed toward finding mathematical expressions that relate a measured quantity of damage to the atmospheric loading of pollutants. The first pollutant/material combination considered is the damage caused by SO_2 to metals, namely zinc (or galvanized surfaces) and base steel. Next the damage caused by SO_2 to exterior paint is addressed. This is followed by short discussions of damage to other materials by ozone and total suspended particulates (TSP).

DAMAGE TO METALS

Metal corrosion is a process which is thermodynamically favored, that is, the oxides have lower free energy than a combination of a pure metal and atmospheric oxygen. However, the rate at which the corrosion reactions proceed is influenced by a number of physical and chemical factors.

As in any chemical reaction system, the corrosion process involves reactions which have a barrier or activation energy preventing immediate completion. The simple reaction of iron and oxygen at ambient temperatures, for example, is very slow. However, alternative pathways, leading to the same products, may have lower barriers and therefore proceed rapidly when conditions are favorable.

The atmospheric corrosion of metals is often dominated by a complex electrochemical process rather than by simple gas solid reactions. With an electrolyte present, small electrochemical cells form on the exposed surface of the metal because of the chemical and/or physical differences of adjacent regions. These electrochemical differences may result, for example, from localized differences in surface stress or slight differences in chemical composition. The potential difference between these local centers results in a current flow which greatly accelerates the oxidation reactions associated with corrosion. Moisture is a necessary ingredient for this type of metal corrosion (Gajendragadkar 1977). If the surface of the metal is dry no current flows even in highly polluted atmospheres. However, if the metal is wet, current can flow and some corrosion will occur even in an unpolluted atmosphere. However, under clean, unpolluted conditions the rate of corrosion is relatively slow.

In some metals, initial reactions produce a tightly adhering layer of reaction products which protects or isolates the underlying material from further reaction with the atmosphere. Aluminum exposed to air forms a layer of nonreactive oxides. Copper forms a green-colored patina made up of a complex mixture of oxides and carbonates. If these protective coatings are undamaged, further corrosion is prevented. However, if the coating is attacked by air pollutants such that they no longer provide an impermeable coat, corrosion of the substrate may be greatly enhanced.

Most ferrous metal alloys (with the exception of stainless steel) do not produce reaction products which protect against further reaction. Common rust is usually only loosely attached to the substrate and is easily penetrated by atmospheric reactants. Some new alloys, referred to as weathering steels, do provide self-protecting coatings, but are not appropriate for use in all cases, and even these alloys are not immune to attack by the different manmade pollutants. Although it is not the only manmade pollutant capable of damaging metals, sulfur dioxide is the dominant pollutant contributing to the significant corrosion of metals. The rate of corrosion may be strongly influenced by the SO_2 concentration. However, a number of other factors are also important. The importance of moisture has already been discussed. Wind and its influence on the flux of oxygen and SO_2 to the material surface can also be important. Sydberger and Ericson (1976) reported that at SO_2 concentrations of between 1 and 100 ppm, the rate of corrosion increased as the flow rate of SO_2 increased through the test apparatus. Therefore it can be expected that the rate of corrosion of metals will depend not only on the concentration of SO_2 but also on the wind speed and wind direction (in relation to the exposed surface).

Time of Wetness

The rapid corrosion of metals occurs primarily during times when the surface of the metal is wet. To better understand the corrosion process and to be able to predict the damage caused to the metal due to corrosion we must be able to estimate the total "time of wetness".

Sereda (1974) reported on a work by Guttman (1968) in which he found different times of wetness of the exterior surfaces of a galvanized sheet steel wall cladding and roof on a storage building. The average percentage time of wetness varied from 51.1 percent on the north facing roof overhang to 14.6 percent on the south facing wall near the roof overhang. Similarly, Sereda (1974) reported large differences among times of wetness, measured by a dew detector, at different locations of a three-story building of the National Research Council (NRC) Laboratory in Halifax, Canada. Guttman reported that the groundward face of an exposed panel was wet for longer periods than the skyward face.

The average time of wetness depends on atmospheric conditions such as temperature variation, relative humidity and the composition of atmospheric particulate matter. Hygroscopic particles or corrosion products may be deposited on the surface and attract moisture. Similarly, rapid fluctuation in the ambient temperature or surface radiation can cause the air to be supersaturated and the water to condense on the surface of the metal.

Haynie (1976) reported that the fraction of time of wetness, based on the experimental work of Guttman, may be expressed as:

$$f_w = \mathrm{EXP}\left[4.04 - \frac{404}{RH_w}\right] \qquad (1)$$

where RH_w is the annual average relative humidity
f_w is the fraction of time that the surface is wet

Hygroscopic particles can cause a surface to become wet at relative humidities below 100%. Based on the results of a study of the corrosion of the metals conducted in St. Louis, Haynie (1980a) defines the fraction of time that the relative humidity exceeds a given critical value, as:

$$f = [(1-K)\ RH]/(100 - KRH) \qquad (2)$$

where RH is the average annual relative humidity
K is constant less than 1
f is the fraction of time that the relative humidity exceeds a set critical value.

For a critical value of 90%, the value of K equals 0.86.

In a more recent study Haynie (1980b) developed an equation by which the fraction of the time that the surface is wet can be estimated from the average annual relative humidity using a different equation:

$$f_w = \mathrm{EXP}\ [-3.35 \times \frac{(100 - RH)}{RH_w}] \quad (3)$$

A comparison between Equation 1 and 3 is given in Table 1 for different average relative humidities. The two equations give similar results especially at higher relative humidities, when the rate of corrosion is highest. Equation 3 (Haynie 1980b) is used in calculations of time of wetness throughout this report.

TABLE 1. COMPARISON OF TIME OF WETNESS CALCULATIONS

Average Relative Humidity (%)	Calculated Fraction Time of Wetness (%)	
	Equation 1 (Haynie 1976)	Equation 3 (Haynie 1980b)
50	1.7	3.5
75	26	33
90	64	69
95	81	84

ZINC AND GALVANIZED SURFACES

On an area basis more zinc is exposed to the atmosphere than any other metal coating (Boyd and Fink 1974). Zinc is applied to ferrous metal surfaces to protect them from corrosion. In fact, about half of the annual world consumption of zinc is for application where resistance to corrosion is the major requirement (Evans 1973). For example, in a marine atmosphere, the corrosion rate of zinc is about 4 percent that of steel (Slunder and

Boyd 1971). A coating of zinc carbonate ($ZnCO_3$), formed by the reaction of zinc oxide with atmospheric carbon dioxide, prevents further corrosion (Slunder and Boyd 1971). In a polluted atmosphere the protective zinc carbonate coating is washed away by a reaction with an acid solution, for example, sulfur dioxide dissolved in condensed moisture, exposing a fresh surface of zinc to further attack. Thus, in a highly polluted industrial atmosphere with an annual average SO_2 concentration greater than 60 $\mu g/m^3$, signs of rust appear on galvanized steel after only 4 years and the surface may be 80 percent rusted after 10 years (Slunder and Boyd 1971). In a clean marine environment, a similar coating will show signs of rusting after 15-25 years and in a clean rural atmosphere no sign of rusting are expected until 30-40 years of exposure (Slunder and Boyd 1971).

Cavender (1971) investigated the corrosion of zinc panels in different atmospheres. A network of 296 monitoring stations in 144 areas was established. The areas were classified as rural areas that are sparsely populated; residential; and commercial areas primarily used for business purposes, usually downtown urban and industrial areas. Each of the monitoring stations included zinc and steel panels, sulfation plates, and a sulfation candle.

The results are summarized in Table 2. It is clear that the rate of corrosion is lowest in a rural atmosphere and highest in a industrial atmosphere. The correlation between the corrosion rate, the relative humidity, and total sulfation rate was lower than 0.5. On the other hand, Thring (1957) reported a high correlation coefficient (0.97) between zinc corrosion and a sulfur dioxide concentration. Similarly Evans (1972), Kucera (1976) and Hudson (1953) reported that the corrosion rate of zinc in a rural area is much lower than in a heavily industrialized area and is well correlated with the sulfation rate.

TABLE 2. CORROSION RATE OF ZINC PANELS EXPOSED TO DIFFERENT ATMOSPHERES (in μm/yr) (Cavender 1971)

		Percentile					
	Minimum	10th	25th	50th	75th	90th	Maximum
TOTAL 1967	0.16	0.4	0.8	1.4	2.9	4.4	17.0
1968	0.10	0.6	1.1	1.9	3.5	4.9	15.4
Background (1968)	0.5	1.0	1.0	1.2	1.4	3.0	3.4
Industrial	0.9	1.0	1.6	2.4	4.5	6.0	15.4
Commercial	0.2	0.6	0.9	2.1	3.7	5.2	7.1
Residential	0.1	0.4	0.09	1.6	2.8	4.6	15.1
Rural	0.2	0.5	0.9	1.3	2.5	3.8	4.2

In an early laboratory study Vernon (1935) reported that at a constant relative humidity of 99 percent in a clean atmosphere, zinc corroded at a rate of 0.5 μm a year. In a similar experiment, Rajagopalan and Ramaseshan (1959) reported a corrosion rate of 2.2 μm/year at 97 percent relative humidity and 0.3 μm/year at 75 percent relative humidity. The discrepancies in the results of these two studies may be explained by the fact that in Vernon's experiments the temperature in the chamber remained constant at 24°C but in the case of Rajagopalan the chamber temperature fluctuated between 28 and 38°C, thus providing opportunities for the condensation of water on the metal surface resulting in an accelerated corrosion rate.

The effect of the various atmospheres on the rate at which the corrosion of zinc changes with time is a function of exposure location. In an industrial urban area, the rate of corrosion increases with time while in a marine atmosphere and in rural areas, the rate of corrosion decreases with time. This can be explained by the fact that in the marine and rural atmospheres a protective coating of zinc carbonate slows the rate of corrosion. In the industrial atmosphere, acidic gases (SO_2) remove the protective coating and form a deposit of zinc sulfate ($ZnSO_4$) on the surface.

Damage Function

To estimate the economic cost of air pollution and the costs and benefits of reducing the ambient concentration one must be able to estimate the degree of damage caused by a given ambient concentration of the air pollutant.

Guttman (1968) proposed that the corrosion rate of zinc panels exposed to the atmosphere is:

$$Y = 0.00546A^{.8152} \times (B + 0.02889) \qquad (4)$$

where Y is weight loss due to corrosion in g/3 in. x 5 in. panel
A is the time of wetness in hours
B is the concentration of SO_2 in ppm

This relation was proposed after an extensive field program in Birchbank, British Columbia in which panels of pure zinc were exposed for different lengths of time to the atmosphere. After the exposure, the corroded layer was removed and the corrosion was determined by loss of weight. During the experiment the degree of wetness was measured by a dew meter and the concentration of SO_2 was measured by a sulfation plate.

Haynie and Upham (1970) found in their 5-year study in eight U.S. cities that the corrosion rate varied linearly with SO_2 concentration and the relative humidity according to the equation:

$$Y = 0.001028\ (RH - 48.8)\ SO_2 \qquad (5)$$

where Y is the corrosion rate in µm/year
RH is the average relative humidity
SO_2 is the average concentration of SO_2 in µg/m^3

This is similar to the damage function reported by Hershaft (1976) ($corr = .000128f(RH)SO_2$, where $f(RH)$ is an unspecified function of the relative humidity). Note that according to this equation the corrosion rate will be zero at an SO_2 concentration of zero. This result contradicts the findings of many researchers, showing that zinc corrosion also occurs in clean atmospheres although at a much slower rate than when SO_2 is present. In a chamber study, Haynie (1976) reported that the corrosion rate of zinc can be expressed as:

$$corr = [.0187\ SO_2 + \exp(41.85-(23240/RT)]\ t_w \qquad (6)$$

where corr is thickness loss in µm
SO_2 is SO_2 concentration in µg/m^3
T is the temperature in ^oK
R is the gas constant (1.9872 cal/g-mole)
t_w is the time of wetness in years

In a recent study Haynie (1980b) summarized the results of a Tennessee Valley Authority (TVA) study and suggested that the galvanized thickness of transmission towers around power generating systems can be expressed as:

$$T = 117.0 - 0.99t \qquad (7)$$

where T is the galvanized thickness of the tower sections
t is exposure expressed in years.
(The initial average thickness of the galvanized coating is 117 µm.)

This expression can be used to determine the thickness of a galvanized coating after a number of years of exposure in the ambient environment. This equation was based on a survey of 537 towers located in rural areas where SO_2 concentrations range from 1 to 12 ppb.

Based on the results of the survey and assuming an average relative humidity of 70.6 percent and a time of wetness equivalent to 25 percent of exposure time, the corrosion rate may be expressed as:

$$\text{corr} = (3.9 + 0.0383\ SO_2)\ t_w \tag{8}$$

where corr is loss of thickness in µm/per year
SO_2 is concentration of SO_2 in µg/m^3(annual average)
t_w is time of wetness in years

In another study on the effect of sulfur dioxide on building material Haynie (1980a) suggested that the damage function of SO_2 to galvanized surfaces can be expressed as:

$$\text{corr} = (2.5 + .02\ SO_2)\ t_w \tag{9}$$

Recommended Damage Function

Table 3 is a comparison between the five damage functions discussed previously. The corrosion rate of zinc in µm/year is given for different average annual relative humidities and SO_2 concentrations. The damage function suggested by Haynie (1970) also gives a corrosion rate which appears to be too low. In addition, Haynie suggests that when SO_2 is equal to zero then corrosion is also zero, even at high relative humidities. These results appear to be inconsistent with other published reports.

Haynie (1976) suggested that the corrosion rate is temperature dependent. Theoretically, even though it is correct that the rate of chemical reactions increase with increasing temperature, the solubility of sulfur dioxide in water decreases with temperature. In contrast, most researchers reported that the observed corrosion rate is not average ambient temperature dependent. The damage function obtained by Haynie (1980a) resulted from the

TABLE 3. COMPARISON OF CORROSION OF ZINC USING FIVE DAMAGE FUNCTIONS ASSUMING ANNUAL AVERAGE RELATIVE HUMIDITIES OF 50% TO 95% AND ANNUAL AVERAGE SO_2 CONCENTRATIONS OF 0, 20, 50 AND 80 $\mu g/m^3$
(Corrosion rate, µm/yr)

Relative Humidity (%) Time of Wetness*	50 307	75 2867	90 6037	95 7344	Annual Average SO_2
Guttman** (1968)	.12	.7	1.4	1.6	
Haynie (1970)	0	0	0	0	
Haynie (1976)	.06	.56	1.2	1.4	0
Haynie (1980b)	.13	1.3	2.7	3.3	
Haynie (1980a)	.08	.8	1.7	2.0	
Guttman (1968)	.15	.9	1.7	2.0	
Haynie (1970)	2.5×10^{-2}	.5	.8	.9	
Haynie (1976)	.07	.7	1.4	1.7	20 $\mu g/m^3$
Haynie (1980b)	.16	1.5	3.2	3.9	
Haynie (1980a)	.1	.9	1.9	2.3	
Guttman (1968)	.19	1.2	2.2	2.6	
Haynie (1970)	6.2×10^{-2}	1.3	2.1	2.4	
Haynie (1976)	.1	.9	1.8	2.2	50 $\mu g/m^3$
Haynie (1980b)	.2	1.9	4.0	4.9	
Haynie (1980a)	.12	1.1	2.3	2.8	
Guttman (1968)	.24	1.5	2.7	3.2	
Haynie (1970)	.1	2.7	3.4	3.8	80 $\mu g/m^3$
Haynie (1976)	.2	1.1	2.2	2.7	
Haynie (1980b)	.24	2.3	4.8	5.8	
Haynie (1980a)	.14	1.3	2.7	3.3	

*Time of wetness was calculated from Equation 2 (Haynie 1980b)

**Guttman expresses his damage function as weight lost in grams for a 3 in. x 5 in. panel

The corrosion rate in µm was calculated as follows:

$$corr = \frac{W}{FA} = .007\ W$$

where corr is corrosion rate in µm/year
W is the weight lost in g/3 x 5 inch-year
A is the area in cm^2 of the test panels

$F = 7.14\ g/cm^3$ is the density of zinc
(Handbook of Chemistry and Physics, 53d edition 1972, p. B-153)

analysis of corrosion to galvanized surfaces using data from several areas. Haynie (1980a) suggested this damage function after analyzing damage to building materials in urban areas. Haynie (1980b) has also suggested slightly different damage functions based upon the type of structure. The deposition velocity to large flat surfaces such as roofing and siding is much less than that for lattice structures used in transmission line towers. In addition, chain-link fencing has a deposition velocity nearly twice as large as that of flat sheets. Based on these differences, the damage function for the rate of zinc corrosion used in this analysis is:

$$C = (A + B\ SO_2)\ t_w \tag{10}$$

where C is the zinc corrosion rate
A is the corrosion rate when wet in a clean environment (2.4 µm/yr)
B is the 0.0225 for roofing and siding and 0.0450 for fencing
t_w is the time of wetness in years

EFFECT OF SULFUR DIOXIDE ON BARE STEEL SURFACES

Most steel surfaces exposed to the outside atmosphere are treated with protective coating to minimize the corrosion damage to the steel itself. However, once the protective surface has been removed by corrosion or erosion, the steel itself will begin to corrode.

The sensitivity of steel to corrosion in an aggressive atmosphere depends on the type and composition of the steel. Copper steel and low alloy copper steel (containing 0.2 to 0.5 percent copper) are more resistant to corrosion in an industrial environment than carbon steel (Larrabee 1959). The addition of 0.03 percent of copper to steel reduces corrosion losses in an industrial area by 20 percent (Larrabee and Coburn 1961). Similar results are reported by Legault and Leckie (1974), Brauns and Kalla (1965), Schwenk and

Ternes (1968), Guttman and Sereda (1968), Hudson and Stanners (1953), and Briggs (1968). Moisture and the natural constituents of the atmosphere, such as sea salt particles, can greatly affect the corrosion rate of steel. The American Society for Testing and Materials (ASTM) reported that a 1/16-inch mild steel panel completely disintegrated after 1 1/2 years of exposure at a test site along the San Francisco coast, while a similar panel at Davis, California, located in a rural area 30 miles from the coast, lost only 2.67 grams after 5 years' exposure. As a result of the study, ASTM (1968) pointed out the importance of site selection and the orientation of exposed panels for any future corrosion studies. For example, the panels must not be exposed in a downwind location close to a rocky beach area where sea salt particles, which are relatively large and do not travel great distances, can greatly influence the rate of corrosion. Briggs (1968) reported that cast steels have greater corrosion resistance than malleable iron and wrought steels in an industrial atmosphere. He also reported that the rate of corrosion decreases with time. A similar dependence of the rate of corrosion on the length of exposure was reported by Upham (1967) from a short-term (3 to 16 months) field study at seven sites in Chicago.

Damage Function

Several damage functions for steel have been reported in the literature. Comparison between these functions are difficult because, unlike damage functions for zinc, the rate of corrosion of steel depends on the length of exposure and the composition of the steel.

Upham (1967) studied the corrosion of low carbon (0.019 percent), low copper (.028 percent), mild steel in the St. Louis and Chicago area, and reported several damage functions for the corrosion rate as a function of the sulfation rate and sulfur dioxide concentration. Different damage functions were reported for each urban area. The damage function also changes with the averaging time for the SO_2 concentration as well as the length of exposure. The different damage functions are summarized in Table 4. The differences between St. Louis and Chicago may be explained by the difference in average relative humidity during the exposure period since relative humidity was not reported by Upham.

Haynie and Upham (1971) reported damage functions for carbon steel, copper-bearing steel and weathering steel:

Carbon Steel

$$y = 9.013 \left[e^{0.00161\,SO_2} (4.768t)^{(0.7512 - 0.00582\,OX)} \right] \qquad (11)$$

Copper bearing Steel

$$y = 8.341 \left[e^{0.00171\,SO_2} (4.351t)^{(0.8151 - 0.00642\,OX)} \right] \qquad (12)$$

Weathering steel

$$y = 8.876 \left[e^{0.0045\,SO_2} (3.389t)^{(0.6695 - 0.00544\,OX)} \right] \qquad (13)$$

where y is corrosion in μm

SO_2 is the annual average concentration of SO_2 in μg/m^3

OX is the annual average concentration of oxidants (ozone) in μg/m^3

t is the time of exposure in years

In a more recent laboratory study (Haynie 1976), it was shown that the rate of corrosion of steel is independent of ozone concentration. Haynie and Upham (1974) reported that the corrosion of enameling steel can be described as:

TABLE 4. DAMAGE FUNCTIONS FOR MILD STEEL
(Upham 1967)

Damage Function	Independent Variable	Location	Length of Exposures	Starting Date
$Y = 1.73\ x + 0.74$	Sulfation rate in mg $SO_2/100\ cm^2$, day	St. Louis	2 months	April 1963
$Y = 1.10\ x + 6.56$	Sulfation rate in mg $SO_3/100\ cm^2$, day	St. Louis	16 months	April 1963
$Y = 2.87\ x - 0.03$	Sulfation rate in mg $SO_3/100\ cm^2$, day	St. Louis	3 months	December 1963
$Y = 74.6\ x + 2.8$	SO_2 concentration in ppm 24-hour average	St. Louis	3 months	December 1963
$Y = 88.6\ x\ 2.8$	SO_2 concentration in ppm 24-hour average	St. Louis	3 months	December 1963
$Y = 18.7\ x + 3.7$	SO_2 concentration in ppm. Mean for the exposure period	Chicago	3 months	September 1963
$Y = 26.8\ x + 6.5$	SO_2 concentration in ppm. Mean for the exposure period	Chicago	6 months	September 1963
$Y = 54.1\ x + 9.5$	SO_2 concentration in ppm. Mean for the exposure period	Chicago	12 months	September 1963

$$\text{corr} = 325 \sqrt{t} \exp [0.00275 SO_2 - (163.2/RH)] \qquad (14)$$

where corr is the corrosion in μm
SO_2 is the annual average concentration of sulfur dioxide in $\mu g/m^3$
RH is the annual average relative humidity in percent
t is the exposure time in years

Similar dependence on the square root of time of exposure was reported by Haynie, Spence and Upham (1976). The corrosion of weathering steel was expressed as:

$$\text{corr} = \left[5.64 \sqrt{SO_2} + e^{\left(55.44 - \frac{31,150}{RT}\right)} \right] \sqrt{t_w} \qquad (15)$$

where corr is the corrosion in μm
SO_2 is the annual sulfur dioxide concentration in $\mu g/m^3$
T is the absolute temperature
R is the gas constant = 1.9872 cal/g-mole
t_w is the time of wetness in years

[Equation 11, the equation for carbon steel, will be used throughout this report when calculating the damage caused by air pollution to bare steel.]

DAMAGE TO EXTERIOR PAINTS BY SULFUR DIOXIDE

Relatively little work has been done in the past to establish a cause and effect relationship for air pollutants on painted exterior surfaces.

In a comprehensive study done by Campbell (1972) of the Sherwin Williams Company, panels painted with different exterior paints (automotive refinish, latex coating, coil coating, industrial maintenance, and oil house paint) were exposed to air pollutants in environmental chambers under accelerated weathering conditions. The panels were exposed to a low (0.1 ppm) and high (1 ppm) concentration of ozone and sulfur dioxide. After exposure the panels were examined by measuring erosion, gloss, surface roughness, and tensile strength. Infrared, attenuated total reflectance (ATR) and a scanning electron microscope were the techniques used to examine the painted surfaces. The panels were examined after 0, 400, 700 and 1000 hours of exposure.

The relative magnitude of the effect of exposure to air pollutants depended on the particular test used to measure the damage to the surface. For example, house paint exhibited the greatest change in properties when tested with the IR-ATR method while automotive paint exhibited the least change. However, the automotive refinish exhibited the largest loss of gloss, while the oil house paint suffered no loss.

In general, the chamber studies at Sherwin Williams indicate that no statistically significant damage was associated with 0.1 ppm exposures, but that the 1.0 ppm pollutant levels did cause measurable effects. It should be kept in mind, however, that an average ambient concentration of 1 ppm SO_2 or ozone is unrealistically high and is not likely to be encountered in the real world for extended periods.

The Sherwin Williams study (Campbell 1972) also included field studies in which coated panels were exposed at four locations listed in Table 5.

TABLE 5. LOCATION OF EXPOSURE SITES FOR THE SHERWIN WILLIAMS STUDY (Campbell 1972)

Location	Environment	Pollution Level (1970 annual average)	
		SO_2	O_3
North-Central North Dakota	Clean-Rural	Low	Low
Los Angeles, California	Urban	Low	High
Chicago	Urban	High	Low
Valparaiso, Indiana	Suburban	Moderate	Low

The damage to the panels was quantified by the various methods already listed. The results were inconclusive since the ranking of the damage within each test site varied widely with the method of measurement.

In other chamber study work, Haynie (1976) exposed oil house paint, vinyl coil coating and acrylic coil coating to high (0.50 ppm) and low (.05 ppm) concentrations of SO_2, NO_2 and O_3. Based on this study, it was proposed that paint erosion is a reliable indicator of damage to painted surfaces and the following damage function was suggested:

$$E = (10 + .03\,(SO_2))\,t_w \tag{16}$$

where E is the erosion in μm/yr
SO_2 is the annual average SO_2 in μg/m^3
t_w is the time of wetness in years

DAMAGE TO RUBBER

Ozone can cause cracks in rubber under stress. The cracks are caused as a result of an ozone attack on the chemical structure of the rubber. Automobile tires are the major rubber product in wide use outdoors. Modern formulations of plasticizers and antiozonides reduces the susceptability of tires to attack by ozone to a point where tread wear is the dominant factor in lifetime. However, the recent development of the long-lasting radial steel-belted tires might reestablish the importance of ozone as a limiting factor on the lifetime of tires. Damage functions relating tire life to ozone concentration are not currently available in the literature. The work of Edwards and Storey (1959) provides a framework for making an initial assessment of ozone concentrations and rubber. They determined the effects of ozone on certain elastomeric formulations used in tire sidewalls containing various amounts of antiozonants under 100 percent strain. The results show that increasing the amount of antiozonants produced significant reductions in the rate of cracking, with increasing amounts of ozone necessary to initiate visible cracks. An exponential relationship between the dose, expressed in ppm multiplied by exposure time, and the percentage of antiozonant, was found:

$$\text{Critical Dose (ppm x min)} = ae^{bz} \tag{17}$$

where a and b are constants dependent on the elastomeric mix
z is the percentage of antiozonant

A version of Equation 17 will be used to relate sidewall cracking and ozone concentrations.

SOILING

In a study in Birmingham, Alabama, Beloin and Haynie (1975) exposed several materials (painted cedar siding, concrete block, zinc, limestone, asphalt shingle and window glass) at five sites. Suspended particulate matter measured using high-volume samplers at these sites ranged from 60 $\mu g/m^3$ to 250 $\mu g/m^3$. The degree of soiling was measured by reflectance and was found to be proportional to the square root of the annual geometric mean of the concentration of suspended particulates for all substrates. The only exception was for the white asphalt shingles where the reflectance was proportional to the concentration. A linear regression of the data resulted in the following damage functions for acrylic emulsion paint:

$$\ln (92.5 - Y) = -0.311 + 0.345 \ln (sp) + 0.612 \ln (t) \tag{18}$$

where Y is the percent reflectance
sp is the average concentration of suspended particulate matter
t is the time in months

For white asphalt shingles the damage function is:

$$\ln (41.8 - Y) = - 4.881 + 0.001 \ln (sp) + 0.545 (t) \qquad (19)$$

It is difficult to measure soiling. Unlike metal corrosion or paint erosion where damage can be measured in loss of thickness, soiling results in reduced aesthetic value which is largely subjective.

ECONOMIC CONSIDERATIONS

The economic costs of air pollution damage to materials may be classified in three categories: direct costs, avoidance costs and aesthetic costs. Direct costs are those costs incurred for the repair or replacement of materials that have been damaged or destroyed by pollution. Materials, such as wood or steel, will rot or rust in the absence of protective coatings. If this damage is significantly accelerated by a pollutant, the increased cost of repair or replacement is a direct cost of the pollution. Sulfur oxides erode and corrode the painted and galvanized coatings used to protect these basic structural materials from the damaging effects of moisture and other natural elements. In these cases, the cost of regular maintenance is the cost paid to avoid the greater costs associated with material failure. For a house, if maintenance is delayed, painted surfaces may require extensive scraping or stripping or even the replacement of rotted boards and siding.

Finally, pollutants may affect the functioning of certain materials without damaging them permanently. Glass, for example, is dirtied by particulate matter in the air, and dirty windows are a source of displeasure to many property owners and renters. It is of course possible to determine the cost of cleaning dirty windows or dirty cars, or soiled buildings, but the benefit to be derived from cleaner materials is often a psychological or aesthetic one. The aesthetic costs of air pollution are real, but these costs are difficult to quantify in the absence of market data that relate the level of cleanliness to property values or rents. The quantification of benefits from reducing air pollution damages to materials depends on the economic behavior of the firm or household responsible for maintaining them.

Homeowners

Families purchase houses to provide shelter and to realize income from an investment. Most homeowners live in more than one house over a lifetime so that they seek to maintain and maximize the value of that property subject to constraints on time, home repair skill, and income.

The decision to maximize the value of the property has a time dimension. Ideally, property values should be maximized just prior to sale so as to realize maximum selling price. However, since most homeowners do not usually know years in advance when they will sell, it proves difficult in practice to perform maintenance on a time schedule that maximizes the net discounted stream of property values at the time of sale. Instead, property owners typically either take frequent small maintenance actions that ensure that the property is close to maximum value at all times or incur little or no maintenance costs until after a decision is made to sell the property.

The choice of these strategies depends upon a number of variables:

- income
- neighborhood pressures
- interest rates

- costs of materials and labor
- penalty costs of infrequent maintenance
- length of stay in the house
- aesthetic tastes and flexibility

The amount of income available to a property owner often affects the type and quality of maintenance. Decisions on whether to install relatively expensive siding or to restore surfaces by less expensive painting will definitely be influenced by available cash flow. Also, higher income families are likely to live in towns and neighborhoods where peer pressure or building codes may limit the homeowner's freedom not to engage in a maintenance strategy, since external costs may accrue to the adjacent properties.

The cost and frequency of maintenance necessary to protect a home from pollution damage are key factors in the decisionmaking process. Cost decisions are based on the type of surface coating and time required to apply the coating. In the case of painting, labor costs are far greater than material costs. Homeowners can choose to do the work themselves or hire professional painters. In the former case, owners must consider the capital costs of the necessary equipment (brushes, ladders and drop cloths) as well as the time required and risk assumed in performing the work themselves. The opportunity cost of time spent painting a home can be measured as the time lost to other activities such as work or recreation. When professional painters are hired, the costs of time and materials incurred by the painters are reflected in the cost and provisions of the contract.

Homeowners have the option of substituting more expensive maintenance-free materials, such as vinyl or aluminum siding, for paints that require periodic renewal. A number of variables affect the present value cost comparison of siding versus paints. Since siding is substantially more costly than painting, higher interest rates weight present expenditures more heavily than future expenditures. The higher initial costs of siding and the fact that contractors must usually be hired to install it may make it difficult for some lower income households to afford. Finally, since siding is expected to last about 25 years, the payback period on the investment may be longer than most homeowners expect to stay in their present home.

Aesthetic tastes are also a factor that may affect the homeowner's maintenance decisions. With painting, the homeowner has the flexibility of changing colors with only the additional costs of more paint and labor to cover the original color.

Commercial and Industrial Property Owners

Commercial and industrial property owners are faced with a decision framework for maintenance activities for property exposed in the outdoor environment which is different from that of homeowners. In a business environment these decisions are taken within a larger cost and investment context with the objective to maximize profits over some time period.

Some of the following variables affect the perceived alternative choices:

- expected economic life of the structure
- costs of maintenance
- interest rates
- penalty costs
- profits and taxes
- zoning laws

For example, the costs of maintaining steel structures are heavily labor intensive. In all cases surface preparation is necessary to clean surfaces before repainting steel. Sand blasting is frequently use to clean rust, grease, dirt, and other foreign materials. Galvanized steel surfaces can be painted before the zinc corrodes and rusting occurs, although thorough surface cleaning is required. Once rusting is well-established in a thin galvanized sheet of the type used on roofing, for example, the reaction proceeds very rapidly and replacement is necessary. On other galvanized materials where minor damage such as rust can be tolerated, as on chain-link fencing, penalty costs are not so severe.

In addition, the real costs of maintenance may depend on whether the work is performed by internal or external labor. If a full-time staff of maintenance workers is hired, the frequency of maintenance may increase rather than allow workers to be idle. The opportunity cost of an idle full-time worker may approach zero, since he will still be paid a regular salary. In some industries, maintenance requirements for essential machinery may shut down the entire plant and free the production staff to perform routine maintenance on both machinery and structures.

Interest rates affect the firm in the same way as the individual decisionmaker. Future costs of maintenance should be discounted at the opportunity cost of capital for each enterprise. For larger firms, whose borrowing costs are lower because of less risk of default, the discount rate reflecting the opportunity costs of capital will usually be less than that of an individual. Lower discount rates and a longer time span can be expected to cause firms to expend greater amounts for maintenance more frequently than individual homeowners.

The profit and tax situation of a firm will also affect the schedule of maintenance. In most cases, maintenance expenditures are not likely to be a high percentage of operating costs so that cash flow is not likely to be a constraint in most years. Maintenance, which is tax deductible, may be undertaken only in profitable years and foregone in years when losses occur.

Another factor that may affect maintenance decisions by the commercial and industrial sector is the building code. Certain building codes or zoning bylaws may require property owners to maintain quality standards for the appearance of buildings. Similarly, these regulations may restrict the choice of materials for the construction of structures. If applicable, these municipal regulations can be expected to provide for a base level of maintenance for all structures in an area regardless of other economic considerations.

Public Sector

Government departments at the local, State and Federal levels are responsible for the construction and maintenance of publicly-owned buildings and structures. Public sector maintenance strategies are influenced by the following variables:

- risk aversion
- cost
- government budget allocations
- interest rates
- penalty costs
- revenue sharing

Government officials are responsible to the public both for the safety and maintenance of public structures, and for the proper management of fiscal resources. In the case of a municipal structure where the public safety has a high priority, government officials are more likely to adopt a strategy that minimizes the risk of a failure, since it is relatively easy to justify additional public expenditures for public safety.

The cost of maintenance, labor and materials is also a major factor in the frequency and quality of maintenance. Where a maintenance department exists, the opportunity cost of using that labor may be low, especially at certain times of the year. It may also make a difference whether certain types of maintenance are contracted and whether the contract is for fixed price or for time and materials.

Amounts of public expenditure, of course, are fixed by budget allocations. For political reasons cutbacks in real dollar allocations can occur thereby compromising the quality of the maintenance effort. For example, prices of goods may rise faster than budget allocations, forcing public authorities to compromise on the quality or quantity of paints or other materials. Like the private sector, the public sector's maintenance decisions are also affected by penalty costs and interest rates.

Aesthetic Costs

Air pollutants may also impair the enjoyment or utility of certain structural materials or monuments without actually damaging the materials. Discolored monuments or dirty windows impose aesthetic disbenefits upon public and private interests. However, the magnitude of those disbenefits is not easily estimated. Public and private decisions regarding the socially best level of maintenance tend to vary greatly with location and time.

MATERIAL IN PLACE

A critical element in determining dollar losses due to pollutant attack is the determination of the amount of material actually exposed to pollutants. The amount of material in place is a key element in any economic damage function. In past studies, the amount of material in place has been estimated by determining the amount of a given material produced during a period equal to the standard use life of that material. An exposure factor is then applied to account for where or how the material is used and its resultant exposure to pollutant damage.

Such an indirect method for estimating materials in place has several weaknesses. The standard use life of a material varies widely with environmental and economic factors. The information available on standard use life is often based more on tax considerations than actual practice. Likewise, exposure factors are difficult to estimate accurately. They are usually based on assumptions of common practice which do not always represent reality.

The most serious weakness is the inherent assumption that once a material is in place, it remains unchanged, except for deterioration. In some cases, such an assumption may be warranted, but in others it totally ignores the impact of practices related to avoidance costs and the changes in those practices with time. Galvanized steel is a good example. Not only has pollutant damage to galvanized steel been thoroughly studied, such damage constitutes a major portion of the costs attributed to pollution of many materials damage estimates.

Zinc coating is added to protect the steel from corrosion (note that the zinc coating would still be needed to protect steel against natural corrosion even if there were no manmade pollutants to consider). For many years galvanized surfaces were not otherwise coated due to poor paint adhesion. During the last 10 years, however, numerous paints and coatings have been introduced into the market which not only adhere to galvanized steels, but also offer excellent pollutant resistance. When bare galvanized steels may be susceptible to pollutant attack, coating such materials (especially for roofing and siding applications) is now common. When a galvanized steel surface shows signs of rust, it is now possible to avoid further damage instead of simply waiting until it is severe enough to warrant replacement. Therefore, although galvanized products are still in extensive use, the amount of zinc actually exposed in heavily polluted areas has greatly decreased; a factor not considered in most material damage estimates to date.

The best determination of pollutant susceptible material exposed in the outdoor environment are two recently completed studies, one by EPA and one by the Electric Power Research Institute (EPRI). In the EPA study, the types of materials in the exterior walls and roofs of residential, commercial and industrial structures in the urban areas of Baltimore, Maryland, and St. Louis, Missouri were categorized. This analysis was based on Sanborn Maps of the structural distribution of materials and a limited field survey.

The results of the EPA study, as analyzed by Haynie (1980c), are presented in Table 6 and 7. Although on the average there are 58.8 m^2 of exterior wall surface area and 40.6 m^2 of exterior roof surface area per capita in these areas, there are significant differences in the amount and distribution of the materials between the two cities. Per capita amounts of the various types of materials employed in wall and roof structures were derived by Haynie from the Baltimore and St. Louis data. Of the specific material defined in the survey, brick and tile were found to be the materials with the greatest distribution, followed by glass (St. Louis) and block, stone, and so on (Baltimore).

The second study was one for the Boston Metropolitan Area performed by TRC for EPRI (Stankunas 1983). Using physical measurement techniques, a sample of exposed painted surfaces, bare galvanized metal, and concrete were made in the Boston Metropolitan Area. Estimates of the total exposed surface

TABLE 6. PER CAPITA AMOUNTS OF STRUCTURAL SURFACES (Haynie 1980c) (m^2/person))

Type	Use	Baltimore	Saint Louis	Total
	Residential	28.4	37.5	34.6
Wall	Commercial	11.9	15.6	13.9
	Industrial	12.1	8.8	10.3
	Total	52.4	61.9	58.8
	Residential	15.8	17.9	16.9
Roof	Commercial	10.0	9.4	9.7
	Industrial	18.8	9.8	14.0
	Total	44.6	37.1	40.6

TABLE 7. PER CAPITA AMOUNTS OF VARIOUS MATERIALS (Haynie 1980c) (m^2/person)

Material	Baltimore	St. Louis	Mean (Standard Deviation)
Steel/Metal	2.3	0.4	1.4 ± 1.3
Block/Stone/Concrete/Slate/Marble	9.8	4.8	7.3 ± 3.5
Brick/Tile	26.4	39.2	32.8 ± 9.1
Wood/Asbestos	7.1	7.8	7.5 ± 0.5
Iron	3.6	0.5	2.1 ± 2.2
Glass	9.9	12.3	11.1 ± 1.7
Other	37.9	34.0	36.0 ± 2.8

area of paint, bare galvanized steel, and structural concrete (not including paving) within the Boston Metropolitan Area are presented in Table 8. The distribution of materials ranged from 0.13 m^2 of painted surface for each square meter of the survey area to 0.012 m^2 of bare galvanized metal for each square meter of the survey area. Assuming an urban area population of 2.798×10^6 people (1980) and an urban area of 2.65×10^9 square meters (103 square miles), per capita amounts of each type of material were derived. These values are presented in Table 8. The per capita amounts of painted surfaces, structural concrete and bare galvanized metal exposed in the Boston Metropolitan Area are 110.1 m^2, 26.6 m^2, and 9.8 m^2, respectively.

TABLE 8. ESTIMATE OF THE TOTAL AMOUNT OF PAINT, BARE GALVANIZED METAL AND STRUCTURAL CONCRETE SURFACE EXPOSED IN THE BOSTON AREA (Stankunas 1983)

Material	Distribution	Total Surface Area	Per Capita
Paint	0.13 m^2 per m^2 of land area	3.07×10^8 m^2	110.1 m^2
Concrete	0.03 m^2 per m^2 of land area	7.43×10^7 m^2	26.6 m^2
Bare Galvanized	0.01 m^2 per m^2 of land area	2.76×10^7 m^2	9.8 m^2

The per capita amounts of material in place are in fairly good agreement between the two studies. The results of the EPRI work show, generally, large amounts of susceptible materials in place, keeping in mind that the EPRI study focused on the actual, exposed surface area of material and all manmade structures. The EPA study, however, was limited to exterior wall and roof material in industrial, commercial and residential structures.

In this study, estimates of pollutant susceptible material in place are based primarily on the EPRI report. The report is specific to the Boston area and to the types of material most affected by ambient pollutant loadings of SO_2, TSP and O_3. In addition, other information on specific structures was used to supplement the information in the EPRI report. The number of rubber tires, the total mileage of chain-link fencing along highways, the number of steel bridges, the number of water tanks, and the number of electrical transmission towers were independently determined as part of this study and used to supplement the EPRI field study results.

SECTION 6

SULFUR DIOXIDE AND STEEL

SUSCEPTIBLE MATERIALS

Metal products identified as being susceptible to SO_2 pollutant damage are traditionally those bare galvanized materials exposed in the Boston urban environment as well as coated steel products. Materials considered for inclusion in the analysis of the urban environment are:

- bare galvanized chain-link fencing installed along highways and public throughfares
- bare galvanized chain-link fencing installed by industrial, commercial and private owners
- bare galvanized and painted steel electrical transmission towers
- galvanized and coated metal building materials
- highway bridges
- highway dividers and guardrails
- street lights and signal poles

A survey of maintenance practices and an estimation of the amount of pollutant-susceptible material in place yielded information regarding the economic significance of air pollution in the deterioration and replacement of these items.

Material In Place

The amount of susceptible material in place in the urban environment can be estimated based on a physical count of structures or per capita estimates based on representative surveys.

The number of electrical transmission towers located within the Boston urban area was provided by the local utility. The transmission system consists of approximately 2,800 structures of which 1,130 are steel and 1,670 are wooden poles. Of the steel structures, 770 are galvanized lattice towers, 170 pole towers, and 190 RIJFRAME towers. The galvanized towers are not coated; however, the other types of towers are painted for aesthetic or safety purposes.

An estimate of the amount of bare, galvanized chain-link fencing located within the urban area was based on a survey of the State highway department as well as application of the results of the EPRI study for the Boston area. A total of 321 miles of fencing was estimated by the highway department to be exposed within the confines of Route 128, the main beltway surrounding the city, approximating the limits of the metropolitan area. Within the city itself and the surrounding urban metropolitan area, the amount of bare galvanized metal other than highway fencing was estimated using the value of 0.013 m^2 of material for each square meter of area. A figure of 2.76 x 10^7 square meters of bare galvanized surface area was derived for the metropolitan area. This figure is inclusive, that is, it covers all bare fences, gutters, roofing and building materials. A substantial fraction of this number represents chain-link fencing, since very little bare galvanized material is used in urban residential and commercial applications because of the aesthetic and maintenance factors associated with its use.

Estimates of the number of street lights, signal poles, signposts, and other metal structures, either galvanized or coated, were obtained from the State and City road departments.

Based on the EPA study of materials distribution in St. Louis and Baltimore, Haynie (1980c) has derived per capita amount of various types of building materials within these two urban areas. The mean value of steel/metal used in walls and roofs of private, commercial and industrial structures within the two metropolitan areas was 1.4 (±1.3) square meters for each person. This value can be used to provide a potential estimate for the painted and coated steel materials found within the structure of an urban area. However, it also considers other types of metals such as aluminum and copper which are not as susceptible to corrosion.

Some double counting may occur in the use of the EPRI and EPA results in the determination of the amount of both bare and coated metal surfaces exposed within the urban area. However, this double counting should be sufficiently small not to bias the results. The only area of duplication would be among structural steel items such as bare gutters and siding. However, so little of this type of material was found in the EPRI survey that duplication between the two studies is not expected to be a problem. Steel and coated steel within the Boston Metropolitan Area is summarized in Table 9.

Maintenance Practices

In general, no preventive maintenance is performed on chain-link fencing by either the public or private sector. Chain-link fencing appears to retain its integrity in the Boston environment for 25 to 50 years. Since it maintains its functional integrity and deteriorates slowly, aesthetic consider-

TABLE 9. SUMMARY OF MATERIAL IN PLACE - BARE AND COATED STEEL - WITHIN THE BOSTON AREA

Item	Distribution
Chain-link Fencing	
Highways	$9.45 \times 10^5 m^2$ (.343 m^2/person)
Commercial, Industrial, Residential	$2.76 \times 10^7 m^2$ (9.8 m^2/person)
Building Materials	$3.86 \times 10^6 m^2$ (1.4 m^2/person)
Transmission Towers - Bare	770
Coated	360
Bridges	600
Highway Sign Posts	3,000
City Sign Posts	1,000
Highway Light Poles	600
City Light Poles	1,500
City Traffic Light Poles	2,500

ations are the predominant feature of any maintenance strategy. Along highways, no fence painting is performed except in areas such as rest stops or scenic views where the aesthetic factor is important. In several of these areas vinyl-bonded fences have become popular due to the wide variety of colors and the increased protection against corrosive elements. Chain-link fencing in the commercial and public sector is likely to be treated in the same manner as the fencing along highways, that is, no maintenance. However, for aesthetic reasons, some painting is possible. Based on data provided by Slunder and Boyd (1971), chain-link fencing should last at least 18 years in an industrial environment before discoloration of the surface prompts painting for aesthetic reasons. In areas visible to the public, it is assumed that the commercial, industrial and private sector will paint fencing to maintain a pleasing appearance. This maintenance strategy will change the nature of the exposure. Instead of a bare galvanized surface, the surface is painted and is thus subject to an entirely new set of criteria damage functions.

The bare galvanized, lattice-type transmission towers used in the Boston area are also maintenance free. As with chain-link fencing, the slow deterioration of the protective surface provides adequate longevity in the Boston environment without maintenance. The newer towers are bare steel over which paint is applied. This surface serves as a protective coating as well as a means to reduce the negative aesthetic impact in populated areas. The life of a coating system in the Boston area is estimated to be 8 to 10 years.

A review of the maintenance practices of the City and the State highway departments regarding guardrails, pole hardware, light posts, traffic signs and parking meters shows that the pollution effects on the use life of such materials are negligible. Guardrails are replaced for safety, design or other external factors before corrosion affects their performance. Improvements in air quality will probably have little impact on maintenance, replacement or the substitution costs of highway guardrails. For street lights, signal poles, traffic signs and parking meters, minimal maintenance practices, substitution of no-maintenance materials such as aluminum, and aesthetic considerations result in a negligible cost factor associated with the effects of air pollution.

Bridge and highway steel structures represent a significant amount of steel exposed to the corrosive effects of atmospheric pollution. Bridge structures are painted with protective coatings to ensure that structural integrity is maintained. Routine maintenance is conducted to ensure these structures remain functional and because of the potentially great replacement and social costs associated with failure. The current protective paint coating is expected to last 8 to 9 years in an industrial environment before repainting is required. However, due to budgetary limitations, maintenance is performed much less frequently resulting in some deterioration of the bridge structure.

Coated metal products such as aluminum and coil coated steel have increased in popularity due to their aesthetic appeal and low maintenance characteristics. Due to a lack of information on lifetimes as well as the fact that these vinyl and acrylic coats succumb very slowly to the effects of SO_2, it is anticipated that these materials are durable enough to exceed their functional use life before any maintenance is required.

Very little bare galvanized steel in gutters and downspouts is present in urban areas. Aesthetic considerations have prompted most owners to match these items with the trim of the structure, providing the material with a protective coat of paint. The damage due to SO_2 to the galvanized surface is therefore dependent upon the durability of the painted surface, not on the zinc coating.

PREVAILING PRACTICE MODEL - BARE GALVANIZED METAL

There are two strategies for dealing with the damage to bare galvanized steel. One is to take remedial action at the first sign of damage by painting the surface with one of the new zinc-rich paints. The other option is to do nothing until the substrate is damaged to the point where it no longer serves its principal function, and then to replace it.

Both strategies are employed. Painting is commonly used where replacement costs would be prohibitive or structure failure catastrophic (for example, galvanized building siding, bridges, and so forth). It is also used where aesthetic effects are important (for example, galvanized chain-link fencing around residential property, gutters and downspouts, and so on) and outweigh the economic benefits of postponing action while the substrate steel rusts out.

For the purposes of the prevailing practice model, the costs are calculated on the basis of the painting/repair strategy rather than the no maintenance/replace strategy. The total amount of bare galvanized material exposed in Boston was calculated using the results of the EPRI study. Assuming that the critical damage level is perceived at 18 years (Slunder and Boyd 1971) and that the annual average SO_2 is 40 $\mu g/m^3$, then the critical damage level may be defined at a corrosion depth of 14 μm, using a variation of Equation 10 and solving for time:

$$t = \frac{CDL}{(A + B\ (SO_2)\ t_w} \qquad (20)$$

where
- t is the time in years
- CDL is the critical damage level
- A is the corrosion rate in a wet, clean air environment, 2.4 $\mu m/yr$
- B is the coefficient for SO_2-induced corrosion, 0.0225 for large flat surfaces and 0.045 for fences
- t_w is the fraction of time of wetness, .2379 for Boston

The time in years that it would take for the same level of corrosion to occur in a clean atmosphere can be predicted using Equation 20 with the SO_2 concentration set to zero. Assuming an annual average SO_2 concentration of 40 $\mu g/m^3$, and a cost for maintenance (painting) of \$12.50 per m^2, incremental damage costs may be calculated for the Boston area due to changes in annual average SO_2 concentrations. Assuming the total amount of bare galvanized metal in place is $2.76 \times 10^7\ m^2$ (Table 9), the total maintenance cost is $\$3.45 \times 10^8$ ($2.76 \times 10^7\ m^2 \times \$12.50/m^2$). The annual maintenance costs are $\$3.45 \times 10^8$ divided by the number of years to the time of first maintenance (Column 2, determined from Equation 20 using a value of

TABLE 10. ANNUAL INCREMENTAL COST (1981,$) OF SO_2 DAMAGE TO GALVANIZED STEEL IN THE BOSTON AREA UNDER PREVAILING PRACTICES OF MAINTENANCE

SO_2 Concentration	Time Before First Maintenance	$1/L_p$	$1/L_o$	Δ	Incremental Cost from Zero
0	23.5	.0425	.0425	0.000	0.00
20	20.3	.0493	.0425	0.007	2.3×10^6
30	18.9	.0526	.0425	0.010	3.6×10^6
40	18.0	.0555	.0425	0.013	4.5×10^6
60	15.9	.0628	.0425	0.020	7.0×10^6
80	14.4	.0697	.0425	0.027	9.3×10^6
100	13.1	.0765	.0425	0.034	11.7×10^6
120	12.0	.0832	.0425	0.041	14.1×10^6

.0225 for B, Table 10). The incremental costs due to SO_2 can be determined using Equation 21.

$$C_p = \left[\frac{1}{L_p} - \frac{1}{L_o}\right] C_o \qquad (21)$$

where C_p is the annual incremental cost due to pollutant damage

C_o is the total replacement or maintenance cost for exposed surface material

L_o is the normal lifetime of material surface in the absence of pollutant (years)

L_p is the actual lifetime of material with pollutant present (years)

The incremental cost due to changes in SO_2 concentrations can be determined using the data presented in the table. For example a change in the annual average SO_2 concentration from 40 $\mu g/m^3$ to 30 $\mu g/m^3$ will result in a savings of $\$9.0 \times 10^5$ annually in the Boston area. This value was obtained from the difference between the incremental damage cost at 40 $\mu g/m^3$ ($\$4.5 \times 10^6$) and the incremental damage cost at 30 $\mu g/m^3$ ($\$3.6 \times 10^6$). Calculation of the incremental benefits or disbenefits resulting from changes in annual average concentrations is dependent upon the current annual average SO_2 concentration experienced within the study area. An existing annual average very different from 40 $\mu g/m^3$ will likely lead to changes in maintenance strategies and even material distributions which would influence the situation. Since only a single area with a single pollutant condition was analyzed, it is not possible to predict the exact nature of modifications in prevailing practice that would occur. However, it is likely that differences in the estimated costs given in

Table 10 represent maximum differences since changes in behavior brought about by changes in the pollutant level would tend to reduce total costs.

The annualized maintenance costs for the galvanized fence can also be based on the total costs for all maintenance activities conducted over the useful lifetime of the material. This strategy is included in the least cost model presented in Section 10. The cost includes the initial painting of the fence as well as the additional repainting which must be accomplished. For example, if a fence, having a useful lifetime of 50 years is painted at 18 years at the current level of pollution and every six years afterward, the total maintenance cost can be based on one initial application of paint at 18 years and 5 succeeding applications at six-year intervals until the 50-year lifetime is reached.

For Boston, the assumptions used in formulating Table 10 are somewhat unrealistic and result in monetary values which represent an upper-bound estimate. These values imply that:

- All property owners follow the same maintenance strategy constantly.
- On an annual basis the same amount of a chain-link fence is always available for maintenance. This implies a rapid, constant turnover of material in place to ensure a fresh stock of fence each year.
- Discounting based on interest rates has not been included in the analysis.

Lower cost estimates associated with incremental damage by SO_2 may be developed by changing these initial assumptions. For example, a range of potential incremental damage costs are presented in Figure 3. The upper bound reflects the assumptions presented above while the lower bound of the range is based on the assumption that only one quarter of the $2.76 \times 10^7 m^2$ of bare galvanized metal is maintained and the remainder is allowed

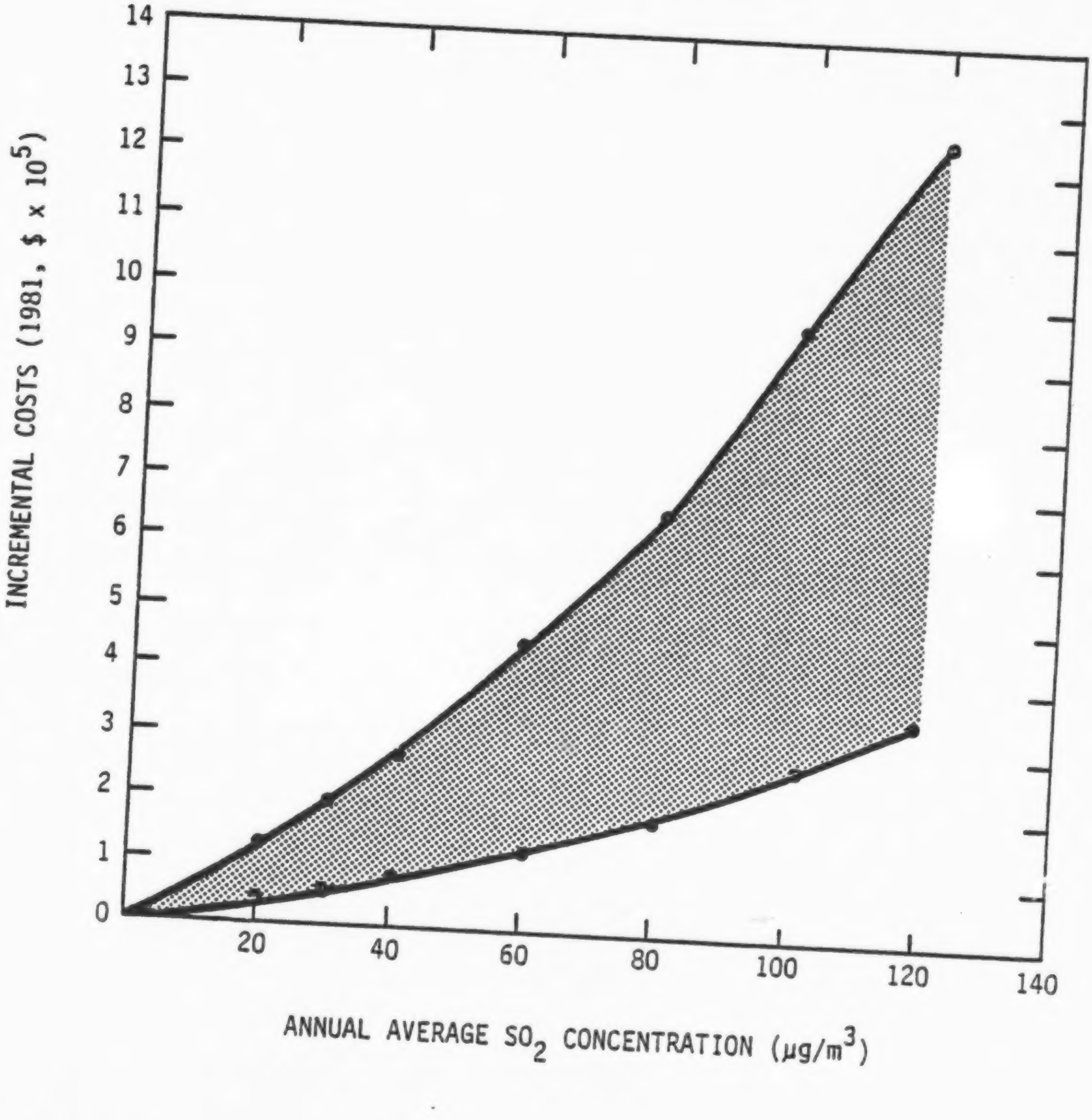

FIGURE 3: Possible range of costs of damage by SO_2 to galvanized steel under prevailing practice.

to rust. The annual costs of maintenance associated with SO_2 air pollution will most probably fall into this category. As with development of the upper-bound value, this approach assumes that corrosion of the material does not result in early replacement.

PREVAILING PRACTICE MODEL - PAINTED STEEL

The coated steel structures in the Boston area consist of building materials, structural steel used in bridges, and painted electrical transmission towers. Coated steel building materials, either coil coated or painted, fit into a different category from the bridge and transmission tower structures. Coil coatings baked onto steel or aluminum are extremely durable and are not adversely affected by ambient levels of pollutants (SO_2, O_3). These coatings have lifetimes of 15 to 20 years before the fading of certain colors becomes apparent. Due to aesthetic considerations, painting may be thought necessary, however, the coating still maintains its functional use, that is, protecting the substrate. As part of the EPRI study (Stankunas 1983), such surfaces are included in the paint category. In addition, for this category of material, it is assumed that necessary maintenance practices are directed to the preservation of the painted surface and that the substrate remains relatively undamaged.

Electric Transmission Towers

As previously stated, no maintenance action is taken with bare galvanized towers. Haynie (1980a) in his analysis of the results of TVA also noted that utilities have not had to face any action regarding maintenance or replacement because most towers are less than 40 years old. The relatively thick galvanized coating allows longevity of these types of structures.

In the Boston area, the electric utility reported that it switched from galvanized steel towers to uncoated steel which requires painting. Environmental concerns over visual degradation caused by transmission lines caused them to employ uncoated steels which can be painted to minimize aesthetic devaluation. The utility is experimenting with painting systems, however, and a zinc oxide primer and organic topcoat are favored. The life of a coating system before maintenance is required, is estimated to be 8 to 10 years. The costs to repaint a structure range from $500 to $2,000 for the smaller 50- to 150-foot towers, $4,000 for the larger RIJFRAME towers, and $20,000 to $25,000 for the giant 400-foot towers.

Replacement costs for towers depend on the structural configuration and strength type. Towers tangent to the line of transmission bear less load and require less steel than towers placed at an angle where the transmission line changes direction. Table 11 provides estimates of installed costs for tangent and angle towers, including both materials and labor.

TABLE 11. COSTS (1981,$) OF REPLACING TRANSMISSION TOWERS

Configuration	Tangent	Angle
Lattice	$ 28,000	$ 62,000
H Frame	26,000	104,000
RIJFRAME	63,000	153,000

A prevailing practice model was then applied to determine the costs associated with SO_2 damage and benefits to be derived from a reduction in annual average SO_2 concentrations. Equation 16 was employed and the annual average SO_2 concentration was set at 40 $\mu g/m^3$ with a maintenance frequency of 10 years:

$$CDL = [10 + .03(SO_2)]\ t_w \times t \qquad (22)$$

where
CDL is the critical damage level
SO_2 is the annual average SO_2
t_w is the time of wetness
t is the maintenance frequency

Application of Equation 22 yields a critical damage level value of 26.6 μm of paint erosion. It should be noted here that the frequency of repainting normally is not dictated by erosion of the painted surface but by peeling, cracking and bubbling of the protective coating. However, for a steel substrate, erosion is the primary damage function. The erosion equation which incorporates the effects of SO_2 is also assumed to be representative of other, naturally-occurring environmental effects which lead to a need for maintenance. The base maintenance cost for the painted transmission towers, \$1.1 x 10^6, was calculated on the basis of 170 pole towers at a maintenance/repainting cost of \$2,000 each and 190 RIJFRAME towers at a cost of \$4,000 each. Annual maintenance costs and incremental costs due to SO_2 damage were calculated using Equation 21 and are summarized in Table 12. As may be seen from the table, only a small amount of the annual repainting costs may be attributed to the effects of SO_2 based on the available physical damage functions.

TABLE 12. ANNUAL INCREMENTAL COSTS (1981,\$) OF SO_2 DAMAGE TO PAINTED TRANSMISSION TOWERS IN THE BOSTON AREA UNDER PREVAILING PRACTICES OF MAINTENANCE

SO_2 Concentration	Maintenance Frequency	$^1/_{L_p}$	$^1/_{L_o}$	Δ	Annual Cost	Incremental Cost
0	11.0	.089	.089	0.00	9.8 x 10^4	
20	10.5	.095	.089	0.01	10.5 x 10^4	6.28 x 10^2
30	10.0	.100	.089	0.11	11.0 x 10^4	1.21 x 10^3
40	10.0	.100	.089	0.11	11.0 x 10^4	1.21 x 10^3
60	9.5	.105	.089	0.02	11.6 x 10^4	1.85 x 10^3
80	9.0	.111	.089	0.02	12.2 x 10^4	2.69 x 10^3
100	8.5	.116	.089	0.03	12.8 x 10^4	3.45 x 10^3
120	8.0	.125	.089	0.04	12.4 x 10^4	4.80 x 10^4

Bridge

The largest single item requiring routine preventive maintenance along highways, and thus the largest portion of the highway maintenance budget, is bridge maintenance.

Bridges, of course, vary greatly in size, structural design and material. Most bridges, however are made of carbon steel which requires regular maintenance to prevent corrosion. Without any preventive maintenance bridges will deteriorate rapidly. Different parts of the bridge structure become structurally unsound sooner than others. Railings and guardrails usually rust most quickly, rendering the bridge unsafe for traffic long before structural members are destroyed. Knowledgeable industry engineers suggest that failure to maintain a bridge structure reduces effective life by 50 percent.

Current maintenance practice in the State of Massachusetts for bridge painting is to use an organic zinc system with a vinyl topcoat rather than the lead silica-chromate system originally used. This system, having a coating thickness of 4 to 5 mils, is expected to last 8 to 9 years in an industrial environment before repainting is required. Consideration is being given to further increasing the specification to include a third coat of high-build vinyl that would increase the coating thickness to 7 to 8 mils with an expected life of 10 to 12 years.

The effectiveness of organic zinc systems depends on the quality of surface preparation. Data are unavailable to date in Massachusetts on how these new inorganic-zinc systems may perform under actual field applications and weathering, particularly in relation to the cost factor.

The current annual maintenance budget for bridge painting within the State of Massachusetts is $400,000. At this level of funding the highway department is limited to painting a specific number of bridges each year. At this level of funding and the typical cost for a bridge, the 3,000 bridges in the State of Massachusetts may be painted only once every 70 years. Additional funding from other accounts is necessary to maintain a more regular maintenance schedule for the structures. In addition, critical transportation links, such as expressways and larger bridge structures, are painted more frequently than smaller bridges.

In recognition of the high costs of bridge maintenance, the Massachusetts State Highway Department is about to specify the substitution of the more durable, coated galvanized steels in new bridge construction. These steels will have a galvanized zinc coating of 1.8 oz/ft^2 and a bonded vinyl overcoat. This new system should withstand a severe industrial environment for 27 to 35 years before rust covers 10 percent of the surface area. Thus it will substantially reduce future maintenance requirements.

However, present budgetary constraints have forced highway departments to postpone painting activities from the 8- to 9-year cycle recommended for protective coatings currently in use to some longer period. This, in turn, complicates the basic assumption of rational decisionmaking in the prevailing practice model. The implication of this practice is that the use life of the highway bridges in Massachusetts is being shortened due to the planned, gradual deterioration of the structure associated with an extended maintenance cycle. A repainting interval consistent with more complete preservation was selected under the assumption that other areas may not face such severe budgetary constraints. A 12-year interval, representing the theoretically rational maintenance interval, was used in the prevailing practice model.

Corrosion of structural steel in bridges occurs first at the edges and joints of each beam rather than at the flat surfaces of the trusses and girders. The coatings tend to be thinner at the edges, more exposed to the effects of weathering and erosion, and subject to expansion and contraction. With a 12-year maintenance cycle, erosion of the painted surface occurs as well as corrosion of the steel substrate. The data from Frondistou-Yannas, (1980) for performance of a oleoresinous coating system (Table 9) in an industrial environment was used in conjunction with damage functions for paint and steel to derive critical damage functions which prompt national maintenance. Using the data in Table 9, the first rust was assumed to occur after 5 years of exposure in the industrial environment and approximately 1 percent rust occurs after 12 years. These periods of time define the critical damage levels for the painted surface and the steel substrate. Application of Equation 22 and Equation 11 yields a paint erosion critical damage level of 13 m and a steel corrosion critical damage level of 40.2 m. These values were then used in conjunction with changes in SO_2 concentrations to determine potential changes in maintenance frequency and benefits or disbenefits from changes in pollution.

Of the approximately 3,000 bridges in Massachusetts, 600 are in the Boston Metropolitan Area. The total cost for painting the 600 bridges was based on an assumed distribution of long bridges, defined as greater than 60 feet in length, and short bridges, defined as less than 60 feet. There are a total of 2,180 steel highway bridges within the State, of which 409 (19 percent) are short bridges and 1771 (81 percent) are long bridges (Yannas 1980). Assuming all 600 bridges in the Boston area are steel, 113 are short bridges and 487 are long bridges. Repainting costs are highly variable and depend upon accessibility and bridge type (truss or girder). A repainting cost of $3,000 was assigned to short bridges and $8,000 was assigned to long bridges. The total cost for painting was therefore derived as $\$4.24 \times 10^6$ for bridges in the Boston area, a figure which includes surface preparation and coating application.

Using the prevailing practice model, assuming that the level of damage brings the required maintenance, the frequency of maintenance, associated annual costs, and incremental costs attributable to SO_2 damage (from Equation 21) were determined. (See Table 13.) Application of the damage function for carbon steel (Equation 11) was used with oxidant levels maintained at an annual average of 0.03 ppm. Using the critical damage levels defined from the assumed 12-year maintenance cycle (5 years for paint and 7 years for steel), the necessary maintenance frequency under different annual average SO_2 concentrations was determined. These maintenance frequencies were used to determine annual cost figures and derive incremental damage costs associated with ambient SO_2 concentrations.

At a zero pollution level, the critical damage level for paint (13 µm) and the physical damage level for steel are reached at 6 and 8 years, respectively. This implies that the current maintenance frequency of 12 years may be extended to 14 years in an SO_2-free environment. Conversely, at an annual average SO_2 level of 80 $\mu g/m^3$ (NAAQS Primary Standard), the critical damage level for paint and for steel are reached at 4 and 6 years, respectively, which implies that the 12-year maintenance frequency must be reduced to 10 years to address the same amount of damage. Depending upon the annual average SO_2 concentration selected, annual maintenance costs range from $\$3.0 \times 10^5$ to $\$4.2 \times 10^5$ for bridge maintenance in the Boston area with incremental damage costs of $\$1.8 \times 10^3$ to $\$12.2 \times 10^3$.

TABLE 13. ANNUAL INCREMENTAL DAMAGE TO STEEL HIGHWAY BRIDGES BY SO_2 IN THE BOSTON AREA UNDER IDEAL PREVAILING PRACTICES OF MAINTENANCE AND INCREMENTAL CHANGES IN COSTS (1981,$)

SO_2 Concentration	Critical Damage Level		Critical Damage Level		$1/L_p$	$1/L_o$	Δ	Annual Cost	Incremental Cost
	μm	time*	μm	time*					
0	13	6	40.2	8	.0714	.0714	.0	3.0×10^5	0.0
20	13	5	40.2	8	.0769	.0714	.055	3.3×10^5	1.8×10^3
30	13	5	40.2	8	.0769	.0714	.055	3.3×10^5	1.8×10^3
40	13	5	40.2	7	.0833	.0714	.012	3.5×10^5	4.2×10^3
60	13	5	40.2	7	.0833	.0714	.012	3.5×10^5	4.2×10^3
80	13	4	40.2	6	.1000	.0714	.029	4.2×10^5	12.2×10^3
100	13	4	40.2	6	.1000	.0714	.029	4.2×10^5	12.2×10^3
120	13	4	40.2	6	.1000	.0714	.029	4.2×10^5	12.2×10^3

*Values expressed in integer year.

SECTION 7

PAINT

INTRODUCTION

Paint functions as both a protective coating designed to limit damage to the underlying substrate as well as to present an attractive surface. Paint is subject to several types of damage that affect its usefulness. Cracking, peeling, erosion and discoloration are all considered unacceptable. Weathering of the painted surface describes the gradual deterioration of the surface, primarily fading and erosion, while peeling and cracking occur due to moisture penetration from inside the structure. Damage to a painted surface is a cumulative effect of the conditions to which the surface is exposed as well as resulting from the properties of the coating itself. Actual conditions include various combinations of temperature, moisture, sunlight and pollution level. The combined effects of climate and the properties of the paint can be quite dramatic. A paint that retains "like-new" properties of coverage and integity of color after 2 years of outdoor exposure in Florida will not survive 2 years in the much harsher climate of the Great Lakes.

Erosion, or the gradual wearing away of the painted surface, is the type of damage most comonly associated with atmospheric SO_2. Discoloration by SO_2 is no longer a significant problem since mercury and lead compounds have been removed from paint and delayed drying or hardening are only problems in unusual circumstances. The level of erosion which is tolerable depends in large part on the sensitivity of the substrate the paint protects. A painted surface is not perfectly uniform. Some portions will be thinner than others. Once the general thickness of the paint has been reduced, the areas which were only thinly covered may be exposed even though the average thickness is not completely removed. Damage to these thinly covered areas of substrate can begin while other areas are still protected. If very small imperfections in the painted surface do not lead to immediate problems, such as with the paint that protects wood, maintenance may be deferred. In other cases, such as with the paint that protects carbon steel, even a few thin spots can lead to the beginning of extensive rusting. Paint is applied over a variety of substrates such as steel, galvanized steel, other metals, wood, brick and concrete. The emphasis in this section is limited to paint applied over wood surfaces, primarily homes. Paint applied over metal surfaces is treated in the sections on damage to metals.

Durability of Coatings

Latex (water-based) and oil-based house paints are the two types of paint commonly used in the Boston residential community. Industrial paints and coil coatings are usually found only in the commercial sector, although coil coatings on vinyl, steel and aluminum are popular replacements for worn out exterior residential siding and paint.

Under equivalent field conditions, good quality latex (water-based) and oil-based paints perform equally, but tradition prevails and most professional painters in the Boston area continue to use oil-based paints. A higher percentage of homeowners, however, use latex paint. The technology of latex paints has improved to the point where most painters concede that good quality latex paints, if properly applied, last as long as oil-based paints. Neither oil-based or latex paints currently in use last as long as paints with lead pigments that were in use until a decade ago.

Proper application and surface preparation is essential for a durable paint coating, whether oil or latex. A criticism of do-it-yourself homeowners is that they limit their application and surface preparation, so that the structure often requires recoating after a short time. Paints must be well-mixed and applied with the proper technique, and surfaces must be scraped, sanded and primed to assure effective adhesion.

Even with careful surface preparation some coatings fail sooner than expected because of site characteristics. Surfaces exposed to sunlight and moisture break down most quickly. The moisture that escapes from a house is also a major cause of coating failure. Clapboard houses are tighter than shingled houses, and generally experience more problems from moisture escaping through the wood and causing paint to peel. Latex paints tend to breathe more easily than oils, and are more durable in high-moisture conditions. Blown-in insulation can be expected to exacerbate the high-moisture problem by causing condensation on the inside surface of exterior walls.

The durability of house paint coatings varies widely, but currently most coatings begin to break down after 3 to 5 years. Formerly, lead alkyd (oil-based) paints could be expected to last 7 to 8 years but the use of such materials has been banned. The substitution of titanium dioxide for lead has reduced the durability of current house paint coating systems. Coatings on new wood surfaces last considerably longer than 3 to 5 years, but recoats on older structures, which predominate in the Boston area, endure less well since they depend on the adhesion between the wood and the initial coating. Coatings around windows and doors often last up to 7 years since less moisture passes through the trim.

The range of 3 to 5 years for the durability of exterior house paint coatings was based on a consensus of opinion of professional painters. The lower figure of 3 years was reported by a siding manufacturer based on a telephone survey of 500 homeowners. The upper figure was frequently quoted by professional painters, who suggested that latex paints lasted perhaps a year less in the Boston area. These values were confirmed by a paint manufacturer, who stated that a latex paint, properly applied by brush at a coverage of 400-450 square feet a gallon, had a lifetime of 4 years before surface erosion prompted repainting.

Industrial coatings and coil coatings on exterior surfaces have much greater durability in both polluted and unpolluted environments. It was reported that a 1-mil thick coil coating on metal has a lifetime of 20 years or greater before the breakdown of the coating necessitates replacement. A 0.8 to 1.0 mil coating with an underlying primer will last even longer. Vinyl coatings, which range from 4 to 8 mils, have a projected lifetime of 30 to 40 years. Although the film itself does not chip, crack or peel, the metal substrate is attacked on the edges of each panel where the coating is thin or nonexistent. Aesthetics tend to be a decisive factor in the use of coil and vinyl coatings. Although the coating retains its primary function, that is, provides a durable, maintenance-free, protective surface, changes in gloss and sheen and the degradation of color can be problems. The causative agents for these aesthetic effects are environmental factors, primarily ultraviolet radiation (sunlight), as well as the qualities of the original pigment, formulation and mixing, and application. Certain colors are prone to varying degrees of degradation. For example, light colors, such as beige, tend to fade and chalk more than a dark brown will while cyanide blues fade more rapidly when exposed to sunlight. In the opinion of manufacturers, damage to coil coatings due to ambient levels of SO_2 is not significant since these films are chemically resistant to attack by this pollutant.

Cost of Painting

Since commercial and industrial sectors generally use paints and other coatings which are much more durable and resistant to SO_2 pollutant damage than those used in the private sector, and labor is an internal factor, the survey on the cost of painting was directed to the private sector, to the homeowner.

Painting costs depend primarily on structural characteristics, the amount of surface preparation, and whether the painting is performed by professional painters or the homeowner. The size of the structure, of course, affects the cost, and height is a key variable because of staging requirements. The Boston area contains a significant number of two- and three-family multistoried structures which are more costly to paint than single-family structures of similar type.

Even more than total surface area the amount of trim area determines the cost of painting. Victorian-style structures are significantly more costly to paint than colonial or cape cod style houses. For typical houses the cost of painting trim amounts to about 50 percent of the cost because of the extra labor and the necessity to put up staging. Thus for many brick and sided homes, the cost of painting the trimwork remains a major maintenance expenditure.

Present structures in the Boston area are primarily wooden frames, and most houses are clad in either wooden clapboards or shingles. No data are available on the existing housing stock, by exterior surface, but it has been suggested than about 10 percent of the structures are protected by maintenance-free materials such as aluminum or vinyl-siding, or asphalt or asbestos shingles. Another 5 to 10 percent is estimated to be masonry: brick or stone. Some of the sided structures also incur costs for the periodic repainting of exposed trimwork.

Painting is a labor-intensive activity, and total costs can be cut dramatically by performing the work oneself. The cost of the paint is usually about 15 to 20 percent of the job cost for professional painters. An average single-family dwelling in the Boston area can be recoated today by professional painters with only spot priming for about $2,000. Two-family houses cost about $2,500 to $3,000 and three-family houses which usually have porches in front and back, cost about $3,500 to $4,000. Victorian houses tend to be larger and often cost more than three-family houses because of the extra trimwork.

For individuals performing the work themselves on a single-family house, the cost of paint and other materials is about $300 to $400. The risk of injury and opportunity costs of time also figure into an individual's decision whether to paint himself. No data are available on what proportion of homeowners in the Boston Area paint their own homes, but information on paint sales supplied by dealers suggests 50 percent.

It requires about 8 to 10 man-days to recoat a single-family dwelling with a modest amount of surface preparation. Assuming homeowners are one-third as efficient as professionals, the hourly cost that equates professional painting with do-it-yourself painting is about $7 to $8 an hour. If homeowners value their leisure time at about 40-50 percent of their wage rate, it implies an annual income (200 man-hours) of $30,000 to $35,000 as the breakeven income, below which homeowners are increasingly likely to paint their own houses. To the extent that ladders or other equipment are unavailable and must be purchased, this income range may be reduced slightly.

Penalty Costs of Delaying Painting

The cost of postponing the decision to paint at regular intervals is initially the extra cost of surface preparation. If no maintenance is performed, paint will eventually blister, peel and dry until it must all be removed by sanding, sandblasting or burning. If the paint is allowed to deteriorate and the wood is exposed to the elements, structural deterioration is inevitable. The first part of the structure to need replacement is likely to be the wooden shingles, which dry up and curl 6 to 7 years after the paint starts to break down. Clapboards begin to rot soon thereafter and need replacement after 8 to 10 years of exposure. Table 14 details the structural consequences and surface preparation costs resulting from the failure to repaint at reasonable intervals.

Until shingles and clapboards begin to deteriorate, most of the additional cost in postponing painting maintenance is due to the increased labor costs of surface preparation. These labor costs increase quickly as the amount of area to be scraped, sanded and primed increases. A few small areas of peeling may be corrected with little loss in time or efficiency by the painting crew, but large areas must be dealt with first before recoating may begin, and this often means an extra day for primer coats to dry.

After 8 years, the surface is likely to have deteriorated sufficiently to require complete repriming. An additional 60 percent of the initial recoating cost is required to complete this extra work. Soon thereafter the entire coating will fail, necessitating the removal of the old coating. This can be

TABLE 14. PENALTY COSTS OF FAILURE TO RECOAT WOODEN STRUCTURES (1981, $)

YEAR	DESCRIPTION	COST	RATIO OF MAINTENANCE COST TO REPAINTING COST (4-year frequency)
0	New coat of paint	$2,000	--
1	--	--	--
2	--	--	--
3	Beginning of blistering on exposed areas such as window sills. Possible touchup recommended.	--	--
4	Slight blistering. May be recoated at minimal cost.	$2,000	1.00
5	Scraping and spot priming required on sun-exposed sides.	$2,100	1.05
6	Moderate scraping and spot priming on all sides.	$2,300	1.15
7	Extensive scraping and sanding on all sides with full priming required on sun-exposed areas.	$2,700	1.35
8	Extensive scraping and sanding on all sides with full priming required of all areas.	$3,200	1.60
9	Coating on sun-expsed sides must be sanded to bare wood.	$3,700	1.85
10	Coating on all side completely dried out. Must be sanded to bare wood.	$4,500	2.25
11	Shingles begin to dry up and curl on sun-exposed sides.	$5,300	2.65
12	Most shingles mustbe replaced on all sides.	$6,200	3.10

accomplished by sandblasting, sanding or burning. Sandblasting is cheaper and less labor-intensive, but its effect on old wood may be to hasten deterioration. Sanding and burning are slower and more costly because they are more labor-intensive. Complete removal of paint increases the cost 2 to 2.5 times the original recoating price.

Once the paint coating breaks down, deterioration of shingles and clapboards begins, and costs of repair increase dramatically. Shingles dry and curl before clapboards begin to rot. The cost of shingle replacement is about $150 a 100 square feet for both materials and labor. Replacing one wall of shingles on a typical house with 650 square feet costs about $1,000. Clapboards are even more expensive at $.33 a linear foot (4-inch width) or $1.00 a square foot just for materials. Replacing a typical exterior side of clapboards, 650 square feet, would cost at least $1,500, including removing old boards, renailing and recaulking by professional carpenters.

Material In Place

The EPRI report (Stankunas, 1983) forms an excellent basis for estimating the amount of painted surface in place within the Boston Metropolitan Area. A total of 3.07×10^8 m^2 of painted surfaces are exposed in the metropolitan area. This figure includes all painted wood, painted brick, painted stone and concrete, painted asbestos, painted shingles, and painted metal. Although there is a wide variety of painted coatings such as latex, oil and coil in use in the urban area, the total amount of each type of coating cannot be determined. However, such a distinction is not crucial for latex and oil paints since each has about the same lifetime and coil coatings represent only a small portion of the total area. As a simplifying assumption, all of the painted surfaces exposed are considered to be of the oil or latex type.

Normal Practice

Determination of normal practice for the painting of exposed, exterior surfaces is a difficult task compounded by a large number of uncertainties. Homeowners tend to paint more often than the commercial/industrial sector. The homeowner will use less expensive paints and will take advantage of his own labor which is free. On the other hand, the commercial/industrial sector is faced with more expensive labor costs and tends to use better materials to minimize the frequency of applications.

The fact that expenditures will occur in the future means that their cost must be discounted at an appropriate rate of interest. The most efficient frequency of painting occurs at the point where discounted present value costs are at a minimum. Different income groups discount future expenditures at different rates of interest. As might be expected, lower income groups discount future costs more heavily than higher income groups that are less constrained by cash flow pressures. Homeowners in lower income groups tend to paint less frequently than those in higher income groups. In an analysis performed by Charles River Associates (CRA) (1981) with different discount rates for different income groups, the frequency of repainting ranged from a minimum of 4 years for the higher income group (>$50,000) to a maximum of 8 years for the lower income group (<$15,000). Such economic considerations make if difficult to define a single prevailing practice.

Painting in the cold weather climate of Boston is seasonal with most painting maintenance undertaken between April and October. Decisions are usually made to paint some time in that 7-month period with the assumption that a delay of a few months is of little consequence. Therefore all painting decisions must be considered in terms of integer years rather than portions of years.

An average maintenance frequency of 5 years was selected as the value which best represents the normal painting cycle in the Boston Metropolitan Area. This assumption is based on the survey of professional painters and the average frequency of repainting for homeowners in various income brackets.

PREVAILING PRACTICE MODEL

The cost associated with painting exterior surface areas was estimated to be $12.50 a square meter. This figure was derived from a factor of $10 a square meter used in a previous study (1978 dollars) and corrected to the Consumer Price Index for 1980. This value fits quite well with the figures developed in the survey of painting practices conducted by CRA. Costs for painting a typical single-family home were found to be approximately $2,000 while two and three-family homes cost approximately $3,500. Assuming 2,000 square feet and 4,000 square feet of exposed exterior surface for a single-family home and multiple family home, respectively, the use of the $12.50 a square meter figure yields repainting costs of $2,322 for the single-family and double that for a multiple-family home.

All of the painted surface areas exposed in the Boston environment was assumed to be on the normal 5-year repainting cycle. The surface area, 3.07 x 10^8 m^2 was then multiplied by the current repainting cost of $12.50 a square meter to determine the total cost for painting all surface areas, $3.84 x 10^9. An annual cost was then developed based on the 5-year repainting cycle. The damage function for paint (Equation 16) was then applied to determine the critical damage level assuming an annual average SO_2 concentration of [illegible] ug/m^3. This critical damage level, which represents erosion of the painted surface, is used as an indicator of surface degradation including cracking and peeling since surface erosion alone is normally not the reason which prompts a decision to repaint. Applying Equation 16 with a 5-year repainting frequency and an annual average SO_2 value of 40 $\mu g/m^3$ yields a critical damage level of 13.3 µm. This critical damage level, designed for normal practice, was then used to determine repainting frequencies given certain annual average SO_2 concentrations. The application of the prevailing practice model, using specified annual average SO_2 concentrations, the derived critical damage level of 13.3 µm, the amount of material in place, and assumed repainting costs are presented in Table 15.

TABLE 15. ANNUAL INCREMENTAL DAMAGE TO PAINT ON WOOD IN THE BOSTON AREA UNDER PREVAILING MAINTENANCE PRACTICES AND INCREMENTAL COSTS (1981,$)

SO_2 Concentration $\mu g/m^3$	Paint Critical Damage		$1/L_p$	$1/L_o$	Δ	Annual Cost	Incremental Cost
	µm	time*					
0	13.3	6	0.17	.167	.000	6.39×10^8	0.00
20	13.3	5	0.20	.167	.033	7.68×10^8	2.53×10^7
30	13.3	5	0.20	.167	.033	7.68×10^8	2.53×10^7
40	13.3	5	0.20	.167	.033	7.68×10^8	2.53×10^7
60	13.3	5	0.20	.167	.033	7.68×10^8	2.53×10^7
80	13.3	5	0.20	.167	.033	7.68×10^8	2.53×10^7
100	13.3	4	0.25	.167	.083	9.59×10^8	7.95×10^7
120	13.3	4	0.25	.167	.083	9.59×10^8	7.95×10^7

*Integer years

A word of caution is in order for reviewing Table 15. The costs associated with repainting and those attributable to the effects of SO_2 for the Boston area are very high, reflecting a precise set of assumptions used in the calculation of these costs:

- A 5-year repainting frequency for all material in place. This is a conservative assumption since it does not account for the effects of more durable exterior coatings.

- The figures expressed in Table 15 reflect that all work is done at premium rates charged by professional painters. A substantial segment of the residential market is maintained by do-it-yourself labor while in the commercial/industrial sector the bulk of the labor is internalized and available at a more favorable cost.

As an example of the degree of uncertainty in these costs, consider the analysis of the residential painting market in the Boston area performed by CRA. Using assumptions on the mix of residential structures and the income classifications of homeowners, opportunity costs, and the costs of labor, both professional and non professional, the annual costs for painting houses in the Boston area at intervals which incur the least costs of maintenance is \$161.8 x 10^6 (1981 dollars). The derived residential values calculated in Table 15 can be compared to this figure by knowing the proportion of painted surface area attributed to the residential market. In his analysis of the results of the EPA material studies for Baltimore and St. Louis, Haynie (1980c) derived a value of 58.8 m^2 a person of structural wall surface for Baltimore, segregated in residential, commercial and industrial sectors, 34.6 m^2 (59 percent) 13.9 m^2 (24 percent), and 10.3 m^2 (17 percent), respectively. As a rough estimate of the distribution of repainting costs in the Boston area, assume that this figure of 59 percent is directly proportional to the amount of painted residential wall surface. Therefore, 59 percent of the total annual repainting costs of \$7.68 x 10^8 from Table 15, or \$4.53 x 10^8 is a crude estimate of the total cost attributable to the residential sector. This figure of \$4.53 x 10^8, derived using the prevailing practice methodology, is 2.8 times the value of \$1.62 x 10^8 for residential painting determined by CRA, and reflects the uncertainties involved in deriving annual costs.

As is apparent from Table 15, the application of the damage function for paint yields small incremental damage costs attributable to SO_2. These costs range from 3.3 percent of the annual repainting costs to 8.3 percent of the annual repainting cost. The value stated in Table 15 represent an upper bound of total cost for repainting and incremental damage due to SO_2.

SECTION 8

OZONE AND RUBBER

INTRODUCTION

The effects of ozone and other oxidants on rubber and rubber-based products is well-known. Stickney (1971) identified a large number of rubber items as potentially susceptible to damage from ozone, including rubber seals, rings, mechanical goods, hose and cable, pharmaceutical goods, and tires. Of all these materials only tires may be considered important since they represent a material system which has:

- A significant exposure to outdoor, ambient levels of ozone coupled with an extended (>1 year) use life
- A significant unit cost
- A large quantity and widespread distribution of material

Economic damage to other rubber items from air pollution is much less important since they represent systems with a much smaller volume of rubber, a lower unit cost, or more importantly, a much lower time exposure to ambient pollution levels. For most of these materials, the quality of the indoor environment and wear and tear in use is more crucial to their economic impact.

Rubber compounds used in tires age over time through the combined effects of light, heat, oxygen and ozone. Vehicle tires, which are the largest product of rubber, are exposed to the damaging effects of all four elements. Heat tends to dry the rubber and cause the rubber to harden and separate from more flexible reinforcing cords. Oxygen and ozone cause rubber to oxidize, resulting in weather checking or cracking. Ultraviolet light can break chemical bonds in the rubber, and cause damage similar to that caused by oxygen and ozone.

The oxidation effects on tires are seen most easily in the cracks that develop along the sidewalls. Natural and butadiene rubbers are coated over the strength-bearing cords in the sidewalls because of their flex properties. However, these rubbers are also susceptible to ozone damage. If cracking proceeds to a point where the cords are exposed to the corrosive effects of humidity, salt, and other roadside elements, deterioration occurs quickly and the tire becomes unsafe. Cracking is an insignificant factor for the tread portion of the tire compared with abrasion and puncture damage.

To protect the rubber in tires, antioxidants and antiozonants are added at a significant cost for each tire. Assuming that current levels of ozone concentration are reduced, economic benefits may be realized either by tire manufacturers, or by tire retreaders. For the manufacturers, reduced ozone levels mean that less antizonants are required to protect tires than are presently used. For retreaders, the quantity of retreadable tire carcasses would increase. It is assumed that the resulting benefits would be passed on to the consumer.

FACTORS THAT AFFECT TIRE COMPOUNDING

Since early in the 1950s, tire manufacturers have added antioxidants and antiozonant compounds to the rubber used in tires, after complaints of tire damage due to weathering. The primary antiozonant in use today is p-phenylenediamine. This compound is currently added to rubber to prevent ozone degradation. Rubber under stress is more susceptible to weathering;

consequently, more antiozonants are added to sidewall compounds than to tread compounds. Antiozonant compounds migrate to the surface where they form a protective barrier neutralizing ozone's corrosive effects. Heat generated during driving causes this migration to occur at a faster rate. Tires at rest are protected from oxidation damage by special waxes that are insoluble in rubber and migrate to the surface as tires cool off.

The actual amount of antiozonants added depends on two factors: ozone concentrations and expected tire life. Tires are designed to withstand the worst ozone conditions likely to be encountered over the life of the tire. In the past, tire manufacturers varied the amount of antiozonants regionally depending on relative ozone concentrations. Now, however, most companies produce for a national market from each plant, and consequently adjust their compounding to worst-case conditions with an appropriate margin for safety. Premature tire failure is costly both in terms of replacement and in the loss of goodwill and customer loyalty and the advantage of producing for a single market generally outweighs the cost. Some manufacturers may still vary the compounding to include more antiozonants in high ozone areas such as Los Angeles, but this could not be verified.

To achieve the necessary durability, all tire manufacturers test their rubber compounds in ozone cabinets to simulate the effects of various environments and to determine their resistance to ozone degradation. Ozone tests are conducted under both static and dynamic (stretched) conditions at concentrations of 0.5 or 1.0 ppm (the National Ambient Air Quality Standards (NAAQS) standard is 0.12 ppm) for 48 hours. Most tires are designed to withstand average ozone concentrations of 0.5 ppm over the expected life of the tire. For the most part, all tires are designed to withstand a high concentration of ozone with the possibility that tires purchased in one area may spend most of their life in another. The current test at 0.5 ppm ozone concentration provides a substantial margin of safety for all but a few high ozone areas of the United States. Even in Los Angeles, where ozone levels frequently exceed the 0.12 ppm maximum NAAQS, the expected lifetime weighted annual average is well below that level at 0.04 ppm.

The second factor that affects the amount of antiozonants is the expected tire life in years. Radial tires currently make up 81 percent of the original equipment market and 56 percent of the replacement market, and have an average lifetime of about 30,000 to 40,000 miles. Assuming an annual average of 10,000 miles for each passenger vehicle, radial tires can be expected to be on the road an average of 3 to 4 years. Bias-belted and bias-ply tires, whose tread life ranges from about 15,000 to 20,000 miles, are expected to be in use 1.5 to 2.5 years. Antiozonants are added in sufficient quantities to resist ozone damage for 5 to 6 years in radial tires, and 3 to 4 years for bias-ply and bias-belted tires.

Antiozonants are added in different proportions according to the susceptibility of the rubber to ozone degradation. About 2 percent (by weight) of antiozonants are added to natural rubber and butiadene sidewall compounds, and about 1 percent is added to more ozone-resistant synthetic rubbers used in the tread. Altogether, about 0.2 to 0.4 pounds of antiozonants are used in original equipment passenger car tires, which weigh 18 to 19 pounds. For heavy-duty truck tires used in tractor trailers, about 1.0 pound of antiozonants are added to a 50-pound tire. At a cost of $2.50 a pound for p-phenylenediamine, the cost of antiozonants is about $0.50 for passenger car tires and about $2.50 for truck tires.

TIRE RETREADING INDUSTRY

The tire retreading industry collects, inspects and retreads serviceable tire carcasses. In 1980 27 million passenger retreads were sold, accounting for 18.4 percent of the total replacement tire market. In truck tires, retreads accounted for 14.5 million units, or 35 percent of the replacement market. Currently, passenger retreads are dominated by bias-ply (12.1 million units) and bias-belted (10.0 million units). However, retreaded radial tires have increased from 3.5 million units in 1976 to 4.9 million units in 1981, and this trend is expected to continue as more radial casings become available to tire retreaders.

The industry secures discarded tire casings from retailers, retreads the casings, and sells the retreaded tires through other retail establishments. The primary raw material is a good quality casing. Casings are inspected at several different points in the collection process. Jobbers in many areas perform a collection function, inspecting tire carcasses and separating those suitable for retreading from those destined for scrap. Jobbers sell carcasses to retreaders who pay about $3.00 for each carcass for passenger tires and $30 to $60 for truck tires.

Retreaders make further inspections. Casings are rejected for several principal reasons:

- Broken belts and torn beads
- Belt-edge separation
- Irregular wear
- Weather checking or cracking
- Deficiencies in the original tire

The principal reasons for rejecting bias-belted and bias-ply casings are broken belts and torn beads. Radial casings are primarily rejected because of belt-edge separation and irregular wear largely attributable to bad alignment. Checking or cracking related to ozone is also cause for rejection, since tires must be able to withstand several more years of wear without cracks developing to the point where the cords are exposed.

Although no data are available to calculate precisely what percentage of casings are rejected for each type of damage, industry sources suggest that rejections due solely to weather checking constitute approximately 10 percent of the total number of rejected passenger car casings.

Total passenger tire casings available for retreading can be estimated from previous sales of new, original equipment and replacement tires. Assuming radial tires last 3 to 4 years and bias tires last 2 years, the number of casings potentially available in 1980 is nearly equal to the sales of radial tires in 1977 plus the amount of bias tires sold in 1978. Table 16 estimates the amount of casings theoretically available nationally for retreading in 1980 and compares it with the amount actually recycled.

TABLE 16. PERCENTAGE OF RETREADS AND DISCARDS BASED ON PAST SALES

	Sales (millions)	Retreaded in 1980 (millions)	Percent	Discarded (millions)	Percent
Radial 1977	92.3	4.9	5.3	87.4	94.7
Bias 1978	102.8	22.1	21.5	80.7	78.5
Total Available in 1980	195.0	27.0	13.8	168.1	86.2

The national estimates for tire sales presented in Table 8 can be translated into local estimates for the Boston area on the basis of relative population. Such a translation, of course, assumes that tire tread wear is similar for urban and rural populations. This assumption would seem to introduce an element of error into the calculations, since urban car owners probably drive fewer miles than residents of rural areas. However, urban "stop-and-go" driving causes tires to wear more quickly than does long-distance driving. Thus it is assumed that tire sales in Boston were proportional to national sales figures, as shown in Table 17.

TABLE 17. AVAILABILITY OF PASSENGER TIRE RESOURCES FOR RETREADING IN BOSTON AREA, 1980

	Sales (thousand units)		Retreading (%)	1980 Retreads (thousand units)		1980 Discards (thousand units)	
	City	SMSA		City	SMSA	City	SMSA
Radial - 1977	230.0	1125.0	5.0	11.5	56.3	218.5	1069.8
Bias - 1978	255.0	1253.0	20.0	51.0	250.6	254.0	1002.4
Total	485.0	2378.0	10.5	62.5	306.9	572.5	2072.2

NOTE: The 1980 population figures used to create this table include the United States: 226,504,825; Boston Standard Metropolitan Statistical Area (SMSA): 2,759,800; Boston: 562,582. The Boston figure is currently being challenged as understating Boston's actual population.

Retreaded tires in New England are less popular than elsewhere. The retreading percentages used in Table 17 to calculate total retreads and discards have been reduced slightly to reflect this trend. As shown in Table 8, total passenger tire retread sales in Boston in 1980 are estimated at 62,500 and 2,072,200 in the city and SMSA, respectively.

ANALYSIS OF BENEFITS

The benefits to manufacturers, and hence to consumers, due to reduced ambient ozone concentrations and subsequent reductions in the levels of antiozonants necessary to provide the same degree of protection from ozone as is currently experienced, must be based on changes in national levels of ozone, not on regional changes. Since major tire companies are organized to produce a certain tire type for a national rather than a regional market, a significant change in national ozone concentrations is required before it would be possible for companies to reduce the present amount of antiozonant additives. Changes in ozone concentrations on a regional basis rather than a national basis will result in benefits to collectors at the local level.

At the current level of antiozonants added to new tires, a reduction in ozone levels in the Boston area would result in less ozone damage to tires, so that a greater number of tire carcasses would be in better condition for retreading. These beneficial impacts would be largely concentrated in the passenger tire retread sector, since truck tires tend to be used so intensively that they are retreaded several times and discarded before ozone damage becomes a consideration.

The benefit formulation for the effects of ozone on rubber tires can be derived by incorporating two concepts. The first is the savings realized in manufacturing and the subsequent direct savings to the public due to the reduction in the amount of antiozonants in new tires. The second is the benefit which would accrue to the retread industry in the salvage value of old, discarded tires and indirectly to the public due to more low-priced tires being available.

Damage Function

The work of Edwards and Storey (1959) on the effects of ozone on elastomeric formulations led to the development of an exponential relationship relating the dose of ozone necessary to initial cracking to the percent of antiozonant present in the tire. The function is:

$$\text{Dose (concentration x time)} = a\, e^{bx} \tag{23}$$

where a and b are constants depending upon the material
x is the amount of antiozonant

Using the results of the laboratory analysis and considering a strain of 20 percent, a more realistic amount of flexing than the 100 percent used by Edwards and Storey, Haynie (1981) has derived the following formula to equate ozone concentration and sidewall checking:

$$R = 75.3\, e^{-1.55x}\, [O_3] \tag{24}$$

where R is the rate of cracking (mm/yr)

$[O_3]$ is the ozone concentration expressed in parts per million (ppm)

x is the amount of antiozonant expressed in percentage of tire weight

Application of Equation 24 to the data gathered from the survey of tire uses and lifetimes in the Boston area resulted in theoretical values of antiozonant amounts consistent with prevailing practice. Assuming an expected useful time life of 3 years for bias-ply tires and 6 years for radial tires, a design ozone level of 0.05 ppm and a use life limit of 2.5 mm of sidewall cracking, the amount of antiozonants, expressed as a percentage by weight necessary to meet these assumptions are 0.97 percent for bias-ply tires and 1.42 percent for radial tires. These values are equivalent to the levels of 1 to 2 percent quoted by manufacturers.

BENEFIT MODEL

The benefit model for the effects of ozone on rubber may consist of two distinct components. The first of these is the manufacturing level, and ultimately the consumer level where the potential savings are related to a reduction in the amount of antiozonants added to the finished product. The second component is the consuming level, where the savings are related to an increasing quantity of tire carcasses available for sale as recapable tires.

Using the equations presented in the previous section, the benefit, expressed in dollars a year, may be determined on either a national or regional level. The benefits cannot be combined since those at the regional level, expressed in more salvageable casings, are a direct result of the longevity attributable to the current amount of antiozonants added to the tires. By changing the amount of antiozonants at the manufacturing level in response to perceived changes in ozone nationally, tires will be designed for a certain use life. This will result in little to no benefit at the regional level. The surplus of recapable tire casings in the regional market-place occurs as a direct result of less damage to the casings given the current antiozonant protection in response to existing national ozone levels.

Manufacturing Savings

Since the ozone resistance of tires is based on national ozone levels, the benefits of the savings from changes at the manufacturing level must be computed from national trends in ozone concentrations rather than on regional changes. As the average ozone level changes from the current value, the amount of antiozonant necessary to maintain the same level of protection (prevailing practice) will also change.

The variables to be considered in the benefit analysis would simply be a function of both the cost savings from the antiozonants no longer required, expressed on a unit basis, as well as the number of tires produced on an annual basis, or:

$$S = f \times P \tag{25}$$

where S is the cost savings at the manufacturing level
f is the incremental cost saving between the current antiozonant level and the future reduced level
P is the annual tire production for which antiozonant protection is required

Equation 24 was applied to determine the percentage of antiozonant necessary to afford the required protection for design use life. Assuming a cost of $2.50 a pound for the antiozonant and a standard 19-pound tire for passenger cars and a standard 50-pound tire for trucks, the cost for each tire may be calculated. These data are presented in Table 18. Hypothetical annual tire production amounts of 100 million passenger car tires (Table 18) and 50 million truck tires yields estimated total preventive costs for ozone protection. Per capita values range from $.59 a person at 0.05 ppm to $.31 a person at 0.02 ppm. These costs are very sensitive to production figures and mixes of tire types. For example, doubling the number representing the annual production of passenger car tires results in doubling per capita costs. Incremental savings (benefits) at the manufacturing level due to changes in ozone concentrations may be approximated using the values in Table 18. These figures represent a very simple approach to a complex problem. Actual savings will be a reflection of many factors including the cost of materials, labor and market conditions.

TABLE 18. ESTIMATE OF PER CAPITA PREVENTIVE COSTS (1981,$) AT THE MANUFACTURING LEVEL FOR ANTIOZONANTS ASSUMING HYPOTHETICAL PASSENGER CAR AND TRUCK TIRE PRODUCTION RATES

Average O_3 Concentration (ppm)	Use Life (yrs)	Cracking Rate (mm/yr)	Antiozonant (%)	Weight of Antiozonant (lbs)	Unit[1] Cost ($)	Production[2]	Total Cost ($)	Per Capita[3] Costs ($/Person)
Passenger Car - Bias-Ply								
.05	3	.83	.97	.18	.46	4×10^7	1.84×10^7	.08
.04	3	.83	.83	.16	.39	4×10^7	1.56×10^7	.07
.03	3	.83	.65	.12	.31	4×10^7	1.24×10^7	.05
.02	3	.83	.38	.07	.18	4×10^7	$.72 \times 10^7$	.03
Passenger Car - Radial								
.05	6	.42	1.42	.26	.67	6×10^7	4.05×10^7	.18
.04	6	.42	1.30	.25	.63	6×10^7	3.78×10^7	.17
.03	6	.42	1.09	.21	.53	6×10^7	3.18×10^7	.14
.02	6	.42	0.83	.16	.40	6×10^7	2.40×10^7	.11
Truck								
.05	2.4	.59	1.20	.60	1.50	5×10^7	7.5×10^7	.33
.04	2.4	.59	1.06	.53	1.33	5×10^7	6.7×10^7	.30
.03	2.4	.59	.88	.44	1.10	5×10^7	5.5×10^7	.17

[1] Unit cost based on a figure of $2.50/lb of antiozonant.

[2] Annual production assumed to be 4×10^7 bias-ply tires, 6×10^7 radial tires and 5×10^7 truck tires.

[3] Per capita costs based on a national population of 2.25×10^8.

Retread Savings

Using the data on tire sales and discards presented in Table 17 and assuming that 10 percent of the discards are due to ozone damage, 1.0698×10^5 radial tires and 1.0024×10^5 bias-ply tires are rejected. With a population of 2.7598×10^6 in the Boston SMSA, the per capita rejection rate is 0.0388 and 0.0363 for the radial tires and bias-ply tires, respectively. Using a salvage value of $3.00 a casing, the per capita costs attributable to the loss of otherwise suitable tire casings is $0.116 and $0.109 for the two types of tires. Assuming as a worst case that all these costs are directly attributable to the average ozone concentration and that the rate of change in cost is uniform for each unit of pollutant, then the costs can be expressed in a linear fashion as:

$$y = m\,[O_3] + b \qquad (26)$$

where y is the per capita costs
m is the cost coefficient (slope) representing the relationship between per capita costs and O_3
$[O_3]$ is the ozone concentration
b is the intercept (origin)

It should be noted here that a basic assumption of Equation 26 is that a linear relationship exists between ozone and rubber cracking and therefore b equals zero. Based on empirical considerations it appears that the polymer-pollutant relationship follows a more exponential function. Higher concentrations of ozone should result in greater damage (cracking) of the sidewall.

For radial tires, the cost coefficient (m) is equal to 3.87 while for the bias-ply tires the value is 3.63. Since the equation is linear, the cost equations for bias-ply and radial tires may be combined in the formula:

$$y = (3.87 + 3.63)\,x \qquad (27)$$

In addition to the cost at the retread level, the consumer also pays for the cost of the antiozonants added to the tires. Assuming a current cost of $2.50 a pound of antiozonant, a uniform tire weight of 19 pounds and a percentage of antiozonant by weight of .97 percent and 1.42 percent for bias-ply and radial tires, the costs for each tire for antiozonants are $.461 and $.675, respectively. Per capita costs for these antiozonants may be determined by multiplying each antiozonant cost figure by the per capita tire sales (Table 17) in the Boston area. Per capita sales of 0.408 radial tires and 0.454 bias-ply tires yield per capita preventive costs of $.209 ($.461 x $.454) for bias-ply tires and $.275 ($.675 x $.408) for radial tires.

The best estimate of the actual cost due to ozone damage and the prevention of such damage at the regional level for radial tires and bias-ply tires may be expressed as:

$$C = \text{Preventative Costs} + \text{Damage Costs } [f(O_3)] \qquad (28)$$

Where C is the per capita cost. Substituting the actual cost values in dollars, Equation 28 may be expressed as:

$$C = 0.484 + 7.50\ x \qquad (29)$$

where
C is the per capita costs ($)
x is the ozone concentration (ppm)

Equation 29 can be used to derive the total cost due to ozone damage at the regional level both at the preventive level (manufacturing) and in the salvage value of casings. Application of this equation for various SO_2 concentrations yields estimated actual per capita costs for damage estimates (Table 19).

TABLE 19. ANNUAL PER CAPITA DAMAGE COSTS (1981,$) AS A FUNCTION OF OZONE CONCENTRATION

Ozone	Estimated Actual Cost	Estimated Optimum Cost
0.010	$ .56	.41
0.015	.60	.52
0.020	.63	.60
0.025	.67	.65
0.030	.70	.70
0.035	.75	.75
0.040	.78	.78
0.045	.82	.81
0.050	.86	.84

Using the survey results, Haynie (1981) has developed an optimal per capita cost function:

$$C_o = 1.632 + 0.265 \ln O_3$$

where C_o is the optimal per capita cost expressed in dollars per year
O_3 is the average ozone concentration in ppm.

Application of this equation yields the estimated optimum per capita costs expressed in Table 19. Except at the very low ozone levels there is very little difference between the estimated actual and the estimated optimum cost. This indicates that manufacturers have done a good job in selecting antiozonant levels for all expected conditions and that there is no significant benefit in changing antiozonant levels to suit particular ozone levels. The estimated actual cost function with its standard deviations should be used to calculate potential benefits of lowering annual average ozone levels. Within two standard deviations the annual savings per person per ppb would be from $0.43 to $1.32.

It is important to understand the uncertainties and potential limitations of these cost estimates which arise in three areas:

- variability in the number of tires sold
- variability in the dollar value of the tire carcass
- accuracy limitations of the regression analysis (Equation 24)

Ignoring the variability in the price of antiozonants and fluctuations in the market of the price of a tire carcass, an upper and lower bound on the per capita costs due to the prevention of ozone damage and failure due to ozone damage may be calculated based on the range of annual tire sales, assumed as ±20 percent of the 1977 and 1978 totals (Table 16) and 76 percent (95 percent confidence limits) for the ozone cost coefficient (Haynie)*. The per capita costs for ozone damage range from a lower bound of $.44 to an upper bound of $.98.

This analysis may be used to establish benefits, keeping in mind:

- the ozone and rubber damage function, for rubber damage by ozone is likely to be nonlinear and not linear as postulated, and some checking will occur even at zero ozone due to heat, oxygen and ultraviolet light. The greatest damage occurs at the higher concentrations of the pollutant resulting in a damage for each unit pollutant that follows an exponential curve.
- the data from the Edwards and Storey (1959) study may be based on a material sample that is markedly different from the tires found in the market-place.
- there is no data on the extent of depth cracking or the variability of such cracking which forms the basis for rejection or selection of casings by the retread industry. Based on the survey of retreaders in the Boston area, an experienced individual will reject a casing subjectively and not from an objective measurement technique. A rejection rate of 10 percent was assumed for this analysis.

The derived per capita costs at the manufacturing level and at the regional level are relatively small, ranging from $.59 to $.31 at the manufacturing level and $.44 to $.98 at the regional level. The incremental cost savings from changes in the current ozone level would be extremely small.

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*Personal communication to E.F. McCarthy, 1981.

SECTION 9

SOILING

ANALYSIS OF DAMAGE

Soiling is defined as the accumulation of particulate matter on the surface of a material exposed in the outdoor environment. Two types of material damage result from soiling. Particulate matter, under the proper conditions, can enhance surface damage through accelerated corrosion and erosion by serving as centers for the condensation of moisture or absorption of gaseous pollutants such as SO_2. The synergistic effects of such combinations have been reported in the literature. The second effect is aesthetic, that is, discoloration of the surface apart from any other enhanced damaging effects. In this case, soiling does not normally affect the functioning of the structure, a coat of paint will continue to protect the substrate, but it does detract from the amenity of the living and working environment.

The soiling of surfaces is a continuous function of time. Immediately after corrective action is taken, such as cleaning to restore a surface to its original appearance, soiling begins again.

The potential synergistic and combined effects of particulate matter will not be considered here since it is a much more complex problem than current pollution/material damage functions address. The emphasis of this section is on the physical soiling of surfaces and the frequency of cleaning to restore original appearance.

An evaluation of the effects of soiling takes into account three factors (Watson, 1978).

- The demand for cleanliness which establishes the threshold or the critical damage level at which action is taken.
- The physical soiling function which relates the accumulation of particulates with the current pollutant levels.
- Actual behavior or normal practice which defines the behavior or response to the pollutant level.

The perceived amount of soiling and the corrective action taken to address it are complicated. First, what is the critical level of damage which prompts remedial activity? It has been shown that the contrast between the original surface appearance and the soiled appearance is an important factor. For a white-painted surface the changes in surface characteristics which reflect on appearance are much more pronounced than for other colored surfaces (Haynie 1974). In response to this, owners probably choose different colors (grey, brown, and so on) and types (flat versus gloss) of paints to reduce aesthetic degradation.

Apart from levels of airborne particulate matter, other effects may be shown to have a profound effect on potential cleaning activities. Mildew has become a problem on painted surfaces because of the ban on toxic fungicides such as mercury in exterior paints. Naturally occurring fading and oxidation effects cause surface changes in materials exposed in outdoors that are independent of airborne particulate matter concentrations.

For painted surfaces, the effects of soiling are often handled by repainting. Significant double counting of the costs associated with pollution damage might result if painting practices and cleaning practices were viewed separately.

Finally, as with most corrective activities related to pollution-induced or pollution-accelerated damage, the frequency of cleaning is associated with and strongly dependent on socioeconomic factors. The ability to pay determines whether corrective actions will be implemented. The ability to pay will also affect the acceptable soiling level for those individuals.

NORMAL PRACTICE

The effects of soiling and corrective action taken to address these effects were studied by contacting professional exterior cleaners in the Boston area. Based on their responses, it was determined that, at least for Boston, the cleaning of exterior surfaces (with the exception of windows) does not occur on a routine basis. The emphasis of this report is therefore on window-washing practices which tend to reflect a more common and systematic response to particulate pollution levels and on washing walls due to soiling or discoloration.

Windows serve several purposes, among them visibility from inside and a space for heat and light to enter. The buildup of dirt or soot on a window pane impedes both these functions, although the visibility impairment probably triggers the window-washing decision. At some threshold of visibility impairment caused by soiling, the disbenefit of a dirty window exceeds the cost of cleaning and therefore the cleaning task is undertaken. Prior to that point there is certainly some loss in amenity, but not enough to warrant marshalling the resources necessary to restore the window to a clean condition. Since the window begins to get dirty as soon as it is washed, there is a continuous loss of amenity until the next washing is justified.

In an environment where the rate of soiling and the costs of window washing do not vary over seasons, consumers can be expected to wash windows on the most efficient schedule dictated by the shape of the cost and disbenefit curves.

In Boston, due to its northern climate, the frequency of window washing is affected by the higher costs of washing during the winter months, therefore most window washing occurs between March and November.

The total costs and frequencies of window washing were considered in the following sectors:

- Residences
- Apartments
- Commercial and government offices
- Retail stores and banks
- Schools
- Hospitals
- Industry

The frequency of window washing and related costs in each sector is presented in Table 20. Most homeowners wash their own windows rather than hire professional cleaners. The frequency of cleaning averages about once a year although it varies from twice a year in some households to once every several years in others. In multifamily units, washing is even more infrequent since these types of structures tend to be multistoried and have a higher proportion of renters than owners. Larger office buildings in the commercial and government sectors tend to have windows washed about three or four times a year. Hotels in the Boston area usually contract for window washing two to four times a year. Many stores and other retail establishments depend on window displays to attract customers. Consequently storefront windows are washed on a regular basis. Due to the rising costs of window washing, most retail establishments have cut back from washing windows once a week to once every two weeks on a year-round basis. Most of this cleaning is in response to general urban dirt from traffic, construction and other activities.

TABLE 20. FREQUENCY OF WINDOW WASHING AND ESTIMATED ANNUAL COSTS (1981,$) FOR THE BOSTON AREA

Section	Frequency	Value of Expenditures ($ x 10^6)
Owner-occupied housing	once/year	14.6
Rental Housing	once/2 years	1.4
Commercial	3 to 4 times/year	0.8
Retail	26 times/year	0.4
Schools	once/2 years	0.7
Hotels	3 to 4 times/year	0.1
Hospitals	twice/year	0.3
Industrial	n.a.	n.a.
TOTAL		18.3

Hospitals and universities within the Boston area have been forced by rising costs to reduce less essential services. Several private universities in the Boston area have cut back on window washing from once a year to once every 2 years. Window washing by hospitals has been reduced, on the average from about four times a year to twice a year (spring and autumn).

Because of the imposed delay in responding to changes in the soiling of windows, small changes in air pollution may be expected to have little or no effect on the frequency or costs of window washing. Thus, the benefits that accrue are in the form of cleaner windows and less visibility impairment at the same cost. Marginal changes in the total costs of window washing due to air quality improvement represent only a minimal estimate of benefits.

The seasonal variation in the costs of window cleaning makes it unlikely that changes in costs will reflect changes in benefits for all sectors. For sectors that typically wash windows only once a year in the spring, small changes in the rate of soiling may intersect the cost curve in the discontinuous or vertical region and result in no change in the frequency of window washing. In other cases where windows are washed frequently, weekly or bimonthly, as in display windows of retail stores, air pollution effects are probably insignificant. Thus, the greatest potential for realizing marginal benefits from reduced soiling in the form of reduced window-washing costs are in those sectors that wash windows from two to four times a year because these sectors have sufficient flexibility to vary the timing of window-washing activities. Where changes in frequency and total costs of window-washing are not implemented in response to reduced rates of particulate soiling, benefits accrue to users in the form of cleaner windows.

As can be seen from Table 20, the highest annual costs are associated with owner-occupied housing units sector (80 percent). Thus the total annual costs for this activity are especially sensitive to the assumptions used to derive this figure. For example, changes in the value of homeowners labor on the number of windows which need cleaning will have a significant impact on these cost estimates.

Watson and Jaksch (1978) in their estimation of household cleaning costs associated with reductions in ambient particulate levels defined three variables necessary in the analysis: a physical soiling function, a behavioral frequency function and an observed expenditure for cleaning. The physical soiling function used in this analysis is the one for white painted surfaces (Equation 18) derived by Haynie and Beloin (1975) while household cleaning costs and the behavioral frequency function are obtained from the Booz Allen study of the Philadelphia area.

Assuming a behavioral frequency of window washing of once a year, Equation 18 was used to define an unacceptable level of dirtiness which would prompt cleaning as necessary. Keep in mind that this damage function is actually for a white-painted surface and that no reliable correlations for window glass arose from the Haynie and Beloin study. However, it is the only mathematical function found in the literature. It is assumed in this approach that the behavioral frequency of washing windows responds to particulate loadings and is not in response to an annual routine that is carried out independently of the degree of dirtiness.

Applying Equation 19, assuming that t equals 12 months and SP equals 59 $\mu g/m^3$, an annual geometric mean (1979) TSP value from the eight monitoring locations within the Boston Metropolitan Area, the critical damage level is defined as a reflectance value of 79 percent. Equation 19 was then used with different particulate levels (annual geometric mean) and a reflectance level of 79 percent to derive changes in the cleaning interval. The results are presented in Table 21. With the assumptions stated previously, the cleaning interval for windows will vary from once every 22 months to once every 10 months for annual geometric mean TSP values of 20 $\mu g/m^3$ to 80 $\mu g/m^3$. Due to the nature of the damage function, a zero pollution value could not be used to assess damage in a clean environment. Therefore, a clean air level of 20 $\mu g/m^3$ was arbitrarily selected as the basis for comparison. Annual cleaning costs for windows attributable to TSP range from \$1.56 x 10^6 at 30 $\mu g/m^3$ to \$11.07 x 10^6 at 80 $\mu g/m^3$.

Using the suggestions of Haynie* that repainting or cleaning occurs when the reflectance value of a white-painted surface is 65 percent, cost estimates for cleaning exterior walls and incremental changes in these

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*Personal communication to E.F. McCarthy, 1981.

TABLE 21. APPLICATION OF THE DAMAGE FUNCTION FOR SOILING TO WINDOW WASHING IN OWNER-OCCUPIED STRUCTURES IN THE BOSTON AREA AND INCREMENTAL CHANGES IN CLEANING COSTS (1981,$)

TSP Annual Geo. Mean (SP)	Reflectance (y)	Cleaning Interval (months)	$1/L_p$	$1/L_o$	Δ	Annual Cost	Incremental Costs
20	79%	22	.546	.546	.000	7.64×10^6	0.00
30	79%	17	.704	.546	.158	9.88×10^6	1.56×10^6
40	79%	15	.800	.546	.254	11.20×10^6	2.84×10^6
50	79%	13	.926	.546	.380	12.90×10^6	4.90×10^6
60	79%	12	1.000	.546	.454	14.00×10^6	6.36×10^6
70	79%	11	1.086	.546	.540	15.27×10^6	8.25×10^6
80	79%	10	1.205	.546	.659	16.80×10^6	11.07×10^6

TABLE 22. APPLICATION OF THE DAMAGE FUNCTION FOR SOILING TO WHITE-PAINTED SURFACES IN THE BOSTON AREA AND INCREMENTAL CHANGES IN CLEANING COSTS (1981,$)

TSP Annual Geo. Mean (SP)	Reflectance (y)	Cleaning Interval (months)	$1/L_p$	$1/L_o$	Δ	Annual Cost	Incremental Costs
20	65%	69	.174	.174	.000	5.34×10^5	0.00
30	65%	55	.218	.174	.044	6.70×10^5	2.94×10^4
40	65%	47	.255	.174	.081	7.83×10^5	6.34×10^4
50	65%	41	.292	.174	.118	8.98×10^5	10.59×10^4
60	65%	37	.325	.174	.151	9.97×10^5	15.05×10^4
70	65%	34	.353	.174	.179	10.85×10^5	19.42×10^4
80	65%	32	.375	.174	.201	11.50×10^5	23.11×10^4

estimates were calculated using Equation 19 and are presented in Table 22. Since not all homeowners clean or repaint in response to dinginess and since other colors apart from white are used in the urban area, the total painted surfaces involved in cleaning or repainting were selected as 5 percent of the total exposed painted surface area or 1.535×10^7 square meters. Washing rather than repainting was considered the only maintenance activity performed since painting because of dirt may also occur at the same time as painting to correct cracking and peeling. Using a cost figure of $2.00 a square meter of surface area, the total maintenance cost attributable to TSP for washing 5 percent of the exposed painted surface areas ranges from $\$2.94 \times 10^4$ at 30 $\mu g/m^3$ to $\$23.1 \times 10^4$ at 80 $\mu g/m^3$.

Significant per capita costs are associated with window washing while lower costs are associated with the washing of white-painted surfaces. The numbers presented indicate the magnitude of the problem due to the assumptions used in the calculation, but not the total cost. A large part of the cost to society of soiling is an aesthetic cost.

In addition, the incremental cost values presented in Tables 21 and 22 do not reflect the assumption of the integer year which was employed in Section 7 for determining the frequency of painting. This assumption was not used in preparing these tables in order to illustrate the changes among potential cleaning intervals and to indicate the amount of aesthetic cost. If the interger-year approach were used, the estimates of incremental costs would change significantly, but would reflect only direct costs.

For example, assuming the concept of an integer year, there would be no difference in the frequency of window washing at annual average TSP levels greater than 50 $\mu g/m^3$. The frequency of 10 to 13 months expressed in

Table 21 would be uniformly expressed as once a year. Similarly, frequencies of 32 months through 37 months expressed in Table 22 would represent a 3-year interval. Thus, no difference in costs would be apparent, despite the fact that the surfaces were noticeably dirtier.

More information is needed to refine these types of cleaning activities including refining the damage functions, surveying behavioral practices, and calculating internal and external maintenance costs.

SECTION 10

LEAST COST MODEL

DESCRIPTION

The least cost model combines physical damage functions and an economic approach using the net present value technique (NPV) to predict the least cost approach to addressing damage to materials exposed outdoors. A variety of maintenance strategies, including no maintenance; the cost associated with each maintenance strategy; and various ambient concentrations of air pollutants may be considered simultaneously. Several variables are the user's input to the model and can thus be changed based on needs and requirements:

- The use life of the material, defined as the period of time that the system of which the material is a part is expected to perform a particular function.
- The value of the material in place reflected by the cost of total repair or replacement.
- The critical damage levels, defined as the amount of damage which prompts a decision for maintenance or replacement of the material.
- The ambient levels of pollutants to which the material is exposed.
- The interest rates for use in calculating the net present value.

The least cost model used in this study was configured to calculate the costs associated with annual average SO_2 concentrations of 0, 20, 40, 60, 80 and 100 $\mu g/m^3$ and uses interest rates of 5 percent, 10 percent and 15 percent in the NPV analysis.

After a pollutant and material are selected, critical damage levels and their associated maintenance practices are identified. For example, galvanized steel siding exposed outdoors is prone to a gradual corrosion of the zinc surface followed by a more rapid corrosion of the steel substrate. A critical damage level, associated maintenance practices and corresponding costs may be defined based on the level of deterioration tolerated. A maintenance strategy intended to preclude a loss of system integrity might be to paint at 10 percent rust, or to paint at 100 percent rust. Alternatively, a no maintenance/replacement strategy might be adopted that assumes the complete replacement of the material after it corrodes to an unacceptable level. For each maintenance strategy selected, it is assumed that the strategy will be continued for the use life of the material.

If the use life of a system is less than the lifetime of one or more of its components, a strategy of no maintenance is automatically chosen. For materials which suffer damage at a rate that prompts repair or replacement prior to the completion of the use life, the costs associated with each maintenance strategy and level of pollutant concentration is evaluated using the net present value technique.

Net Present Value Analysis

The net present value method of analysis that is used in the construction of the least cost model is based on the potential value of money invested at a given rate of return. If the money earns interest, to have a dollar a year from now, one needs to have an amount that is somewhat less than a dollar to invest today.

If one has P dollars now and invests it so an "i" percent return is realized then for n years, the value (V) of the investment is determined as follows:

$$V = P(1+i)^n \tag{30}$$

P dollars today is equivalent to $P(1+i)^n$ dollars n years later. Conversely, P dollars n years from now is equivalent to $\frac{P}{(1+i)^n}$ dollars today. That is, P dollars n years from now should be discounted by the factor $\frac{1}{(1+i)^n}$ to their present day equivalent. The latter is the net present value of the cost n years from now, or:

$$NPV = \frac{P}{(1 + i)^n}$$

The use of this method allows the calculation of a single value (the net present value) from a stream of future costs. The calculations are done in noninflated dollars so that the rate of return must also be expressed in noninflated dollars.

LEAST COST MODEL FOR BARE GALVANIZED STEEL

The least cost model developed for bare galvanized steel employed the physical damage functions expressed in Equation 10 for chain-link fencing and structural galvanized steel. These physical damage functions were used in conjunction with critical damage levels and corresponding maintenance strategies defined as painting at initial rust, painting at 10 percent surface rust, painting at 100 percent surface rust, and a strategy of no maintenance (rust through). A use life of 75 years was selected for the calculation of the least cost strategy.

The flow of the model is presented in Figure 4. The damage function for either type of galvanized steel material is used to define a value of t, the number of years until a critical damage level is reached, based on the maintenance strategy selected. This interval is compared to the use life of the material to determine if:

- The use life of the material is less than the lifetime of the material. If so, no maintenance or replacement is required.
- The use life of the material is greater than the lifetime of the material. Maintenance or replacement is then required and the frequency of that maintenance is dependent upon the strategy selected.

For the painting strategies for zinc or steel, a repainting interval of 6 years was selected following the initial application of paint. These values were selected for simplicity in the calculation of net present value. A constant dollar figure (1981,$) was used for the cost of repainting.

Assuming an annual average SO_2 value and a maintenance strategy with a corresponding critical damage level, a value of t can be determined using the method described above. Subtracting the value of t from the use life yields the period over which a maintenance practice such as painting must be employed. This period, divided by the prescribed maintenance interval, yields the number of maintenance activities required over the use life of the material. For example, the initial rust of a galvanized chain-link fence may be reached after 35 years of exposure at an annual average SO_2 level of 20 $\mu g/m^3$. Therefore, given a useful lifetime of 75 years, maintenance must be performed over the next 40 years. With a maintenance frequency of 6 years, the fence will experience a total of 6 paintings over its useful lifetime. At an exposure to a higher annual average SO_2 level, 60 $\mu g/m^3$, initial rust may be reached after 15 years, prompting 10 painting intervals over the useful lifetime.

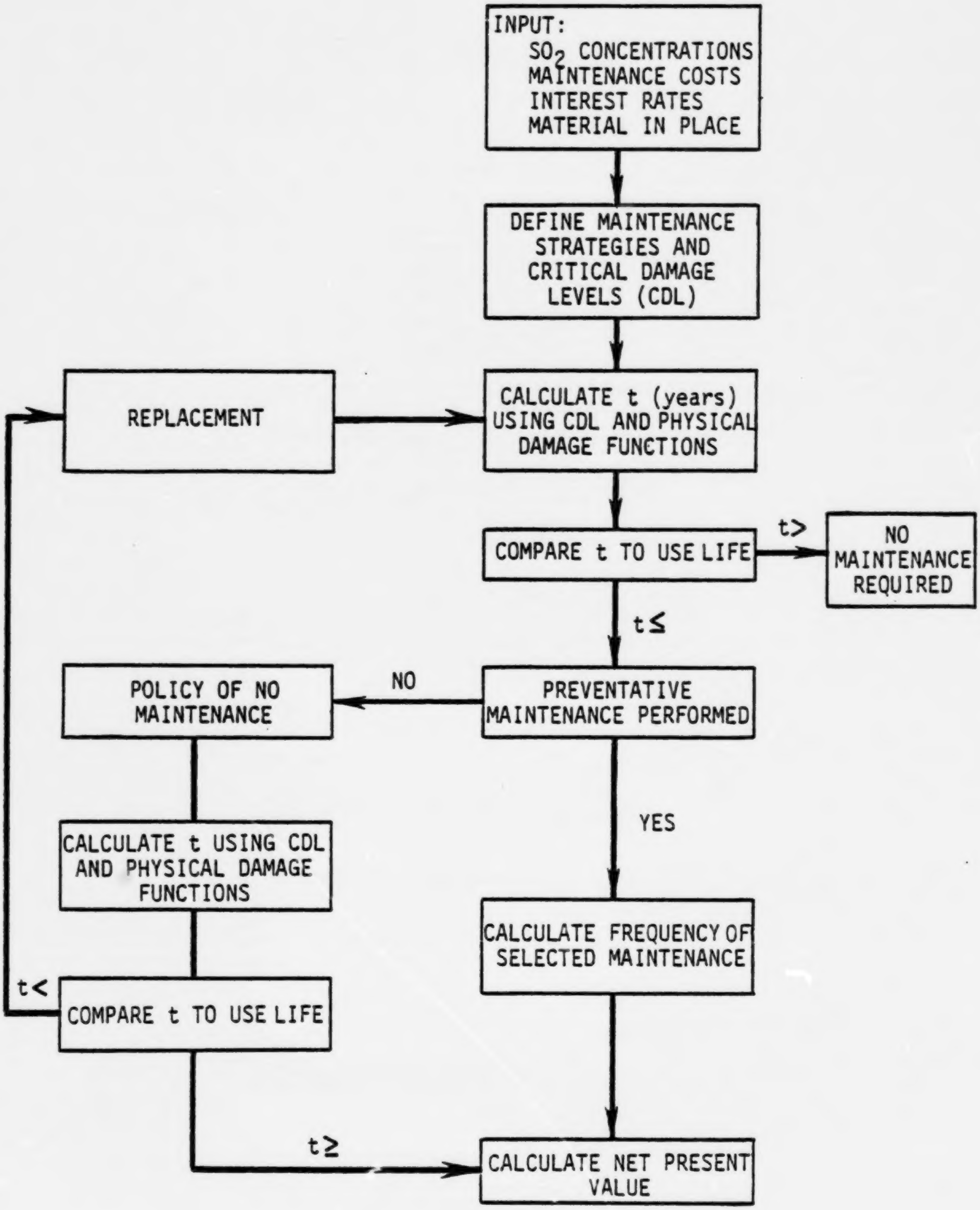
INPUT:
SO2 CONCENTRATIONS
MAINTENANCE COSTS
INTEREST RATES
MATERIAL IN PLACE
DEFINE MAINTENANCE STRATEGIES AND CRITICAL DAMAGE LEVELS (CDL)
REPLACEMENT
CALCULATE t (years) USING CDL AND PHYSICAL DAMAGE FUNCTIONS
COMPARE t TO USE LIFE
t>
NO MAINTENANCE REQUIRED
t≤
NO
POLICY OF NO MAINTENANCE
PREVENTATIVE MAINTENANCE PERFORMED
YES
CALCULATE t USING CDL AND PHYSICAL DAMAGE FUNCTIONS
CALCULATE FREQUENCY OF SELECTED MAINTENANCE
t<
COMPARE t TO USE LIFE
t≥
CALCULATE NET PRESENT VALUE

Figure 4. Least cost model flow for galvanized steel and painted steel material.

The cost associated with the selected maintenance strategy and the frequency of maintenance over the use life of the material may then be used in the net present value analysis. The total amount of bare galvanized metal in place, 2.76×10^7 m^2, was arbitrarily split into two categories: structural material (25 percent) and chain-link fencing (75 percent). Costs, by material type, for each maintenance strategy were replacement costs of $\$10/m^2$ and $\$18/m^2$ for structural galvanized steel and chain-link fencing, and painting costs of $\$4/m^2$ for a 10 percent rust surface and $\$8/m^2$ for a 100 percent rust surface.

The results of the net present value analysis for chain-link fencing and structural galvanized steel are presented in Table 23. For each material use, the net present value for each of three maintenance strategies is calculated at six levels of annual average SO_2 and three interest rates.

Galvanized steel fencing and sheets are considered for analysis applying a use life of 75 years. The maintenance strategies selected are the no maintenance strategy (strategy 1), painting at 10 percent surface rust (strategy 2), or painting at 100 percent rust (strategy 3). A value of t, defined as the number of years until a critical level of damage is reached, is determined using the physical damage function for the material. For strategy 1, t must be calculated based on both zinc erosion and steel corrosion. Therefore, t is computed using a critical damage level of 30 µm for zinc erosion and the physical damage function expressed in Equation 10, followed by a steel corrosion of 65 µm calculated using the physical damage function for carbon steel. For strategies 2 and 3, zinc erosion rates of 20 µm and 30 µm are used as the critical damage levels for maintenance action as presented in the last three columns of both tables. For all three strategies, the NPV analysis indicates that strategy 1 is the least expensive approach and, for the higher interest rates, strategy 3 is less expensive

TABLE 23A. LEAST COST (1981,$) MODEL RESULTS FOR GALVANIZED STEEL FENCING IN THE BOSTON METROPOLITAN AREA USING THREE MAINTENANCE STRATEGIES OF (1) NO MAINTENANCE, (2) PAINT AT 10% RUST, AND (3) PAINT AT 100% RUST.

MATERIAL: GALVANIZED STEEL - FENCING
MAINTENANCE STRATEGY: 1

SO2 LEVEL	USE LIFE	t	MAINTENANCE ACTIVITIES	NPV ($K)		
				5%	10%	15%
0.0	75.0	73.1	1	10525.4	351.5	13.7
20.0	75.0	57.3	1	22760.8	1586.0	124.4
40.0	75.0	47.7	1	36287.2	3944.5	473.2
45.0	75.0	45.8	1	39722.2	4706.8	613.2
50.0	75.0	44.1	1	43157.3	5534.7	777.7
60.0	75.0	41.1	1	50002.0	7378.8	1185.6
80.0	75.0	36.2	2	74305.3	12131.2	2363.0
100.0	75.0	32.4	2	92293.4	17724.6	4058.0

MATERIAL: GALVANIZED STEEL - FENCING
MAINTENANCE STRATEGY: 2

SO2 LEVEL	USE LIFE	t	MAINTENANCE ACTIVITIES	NPV ($K)		
				5%	10%	15%
0.0	75.0	35.0	6	18302.7	3046.4	623.9
20.0	75.0	25.5	8	33577.4	8010.1	2422.4
40.0	75.0	20.0	9	50009.8	14430.0	5375.2
45.0	75.0	19.0	9	54218.8	16187.3	6259.0
50.0	75.0	18.1	9	58455.6	17991.7	7191.6
60.0	75.0	16.5	9	66993.8	21721.2	9187.1
80.0	75.0	14.0	10	84309.4	29553.8	13602.6
100.0	75.0	12.2	10	101698.0	37740.2	18442.8

MATERIAL: GALVANIZED STEEL - FENCING
MAINTENANCE STRATEGY: 3

SO2 LEVEL	USE LIFE	t	MAINTENANCE ACTIVITIES	NPV ($K)		
				5%	10%	15%
0.0	75.0	52.5	3	13814.1	1114.5	107.2
20.0	75.0	38.2	6	30372.4	4455.0	797.4
40.0	75.0	30.0	7	49770.7	10042.2	2530.6
45.0	75.0	28.5	7	54894.2	11726.5	3143.9
50.0	75.0	27.1	7	60098.8	13507.8	3827.5
60.0	75.0	24.7	8	70722.0	17330.2	5397.2
80.0	75.0	21.0	8	92576.2	25824.9	9268.5
100.0	75.0	18.3	9	115024.0	35173.9	13960.7

TABLE 23B. LEAST COST (1981,$) MODEL RESULTS FOR GALVANIZED SHEET STEEL IN THE BOSTON METROPOLITAN AREA USING THREE MAINTENANCE STRATEGIES OF (1) NO MAINTENANCE, (2) PAINT AT 10% RUST AND (3) PAINT AT 100% RUST.

MATERIAL: GALVANIZED STEEL - SHEET
MAINTENANCE STRATEGY: 1

			MAINTENANCE	NPV ($K)		
SO2 LEVEL	USE LIFE	t	ACTIVITIES	5%	10%	15%
0.0	75.0	73.1	1	1952.3	65.2	2.5
20.0	75.0	63.3	1	3145.2	165.5	9.9
40.0	75.0	55.9	1	4513.9	335.2	27.9
45.0	75.0	54.3	1	4877.2	390.0	34.9
50.0	75.0	52.8	1	5247.7	449.9	43.0
60.0	75.0	50.0	1	6007.3	585.9	63.4
80.0	75.0	45.2	1	7586.6	924.4	123.7
100.0	75.0	41.2	1	9222.2	1353.6	216.4

MATERIAL: GALVANIZED STEEL - SHEET
MAINTENANCE STRATEGY: 2

			MAINTENANCE	NPV ($K)		
SO2 LEVEL	USE LIFE	t	ACTIVITIES	5%	10%	15%
0.0	75.0	35.0	6	7736.7	1287.7	263.7
20.0	75.0	29.5	7	10878.1	2238.7	576.4
40.0	75.0	25.5	8	14193.3	3385.9	1024.0
45.0	75.0	24.6	8	15041.9	3697.9	1155.7
50.0	75.0	23.8	8	15896.9	4018.7	1294.9
60.0	75.0	22.4	8	17624.2	4684.5	1594.7
80.0	75.0	20.0	9	21139.4	6099.6	2272.1
100.0	75.0	18.1	9	24709.5	7605.2	3039.9

MATERIAL: GALVANIZED STEEL - SHEET
MAINTENANCE STRATEGY: 3

			MAINTENANCE	NPV ($K)		
SO2 LEVEL	USE LIFE	t	ACTIVITIES	5%	10%	15%
0.0	75.0	52.5	3	5755.9	464.4	44.7
20.0	75.0	44.2	5	9006.7	1032.3	142.6
40.0	75.0	38.2	6	12655.2	1856.2	332.3
45.0	75.0	37.0	6	13615.7	2100.2	396.6
50.0	75.0	35.8	6	14592.5	2358.6	468.1
60.0	75.0	33.6	6	16590.6	2916.7	633.4
80.0	75.0	30.0	7	20737.8	4184.3	1054.4
100.0	75.0	27.1	7	25041.2	5628.3	1594.8

than strategy 2. Interestingly, for a galvanized steel fence, Strategy 3 is less expensive than strategy 2 at SO_2 values of less than 45 $\mu g/m^3$ and an interest rate of 5 percent, while at higher SO_2 values than the opposite is true. The results given here should be considered only as indicators of the total impact of strategy decisions and not as precise determinations of costs.

LEAST COST MODEL FOR PAINTED METAL SURFACES

For painted metal surfaces the least cost model was directed to material used in highway construction (bridges) and painted metal used in structural applications. No other painted metal surfaces were considered in this analysis. To predict the least cost approach, the model incorporates the critical damage function for paint (Equation 16) and carbon steel (Equation 11), preselected maintenance strategies and critical damage levels, and a net present value analysis in conjunction with several levels of annual average SO_2 and discount rates.

For painted steel used in structural applications, four maintenance strategies were considered: paint at initial rust (strategy 1), paint at 50 percent rust (strategy 2), paint at 100 percent rust (strategy 3), and no maintenance (strategy 4). A 100 µm-thick coating was assumed, corresponding to a typical industrial two-coat system. For structural steel, initial rust was assumed to occur when 60 µm of the paint thickness was lost, 50 percent rust was assumed when 75 µm of thickness was lost, and 100 percent rust when 90 µm was lost. For the no maintenance strategy, the steel substrate was allowed to go to 100 percent rust; Equation 11 for carbon steel was used to define the time to total failure, defined as a nominal thickness loss of 1,000 µm.

For painted steel used in highway bridges, a similar set of maintenance practices and associated critical damage levels were selected: paint at initial rust (1), paint at 50 percent rust (2), paint at 100 percent rust (3), and no maintenance (4). A 5-mil thickness (125 μm) was assumed for bridge paint and critical damage levels were defined using the work of Frondistou-Yannas (1980) to determine the time elapsed to each degree of rust. The differences between the models for the two material applications rests with the values of critical damage for each maintenance strategy. Calculations for painted steel are performed in a manner similar to that used for the bare galvanized metal, therefore the flow is similar to that presented in Figure 5. A physical damage function is used to calculate a value for t based on the selected maintenance strategy and the annual average SO_2 value. The use life of the material as well as the maintenance frequency was used to determine the number of required maintenance activities over the lifetime of the material. The costs associated with each maintenance strategy and material application are presented in Table 24. As in the model demonstration for galvanized steel, the cost figures should not be considered as precise estimates.

TABLE 24. COSTS (1981,$) ASSOCIATED WITH EACH MAINTENANCE STRATEGY FOR PAINTED STEEL IN HIGHWAY AND STRUCTURAL APPLICATONS

Maintenance Strategy	Bridges Long	 Short	Structural
Paint at First Rust	80,000	8,000	$ 8/m^2$
Paint at 50% Rust	135,000	13,500	$12/m^2
Paint at 100% Rust	180,000	18,000	$18/m^2
No maintenance	1.0×10^6	$.25 \times 10^6$	$22.5/m^2

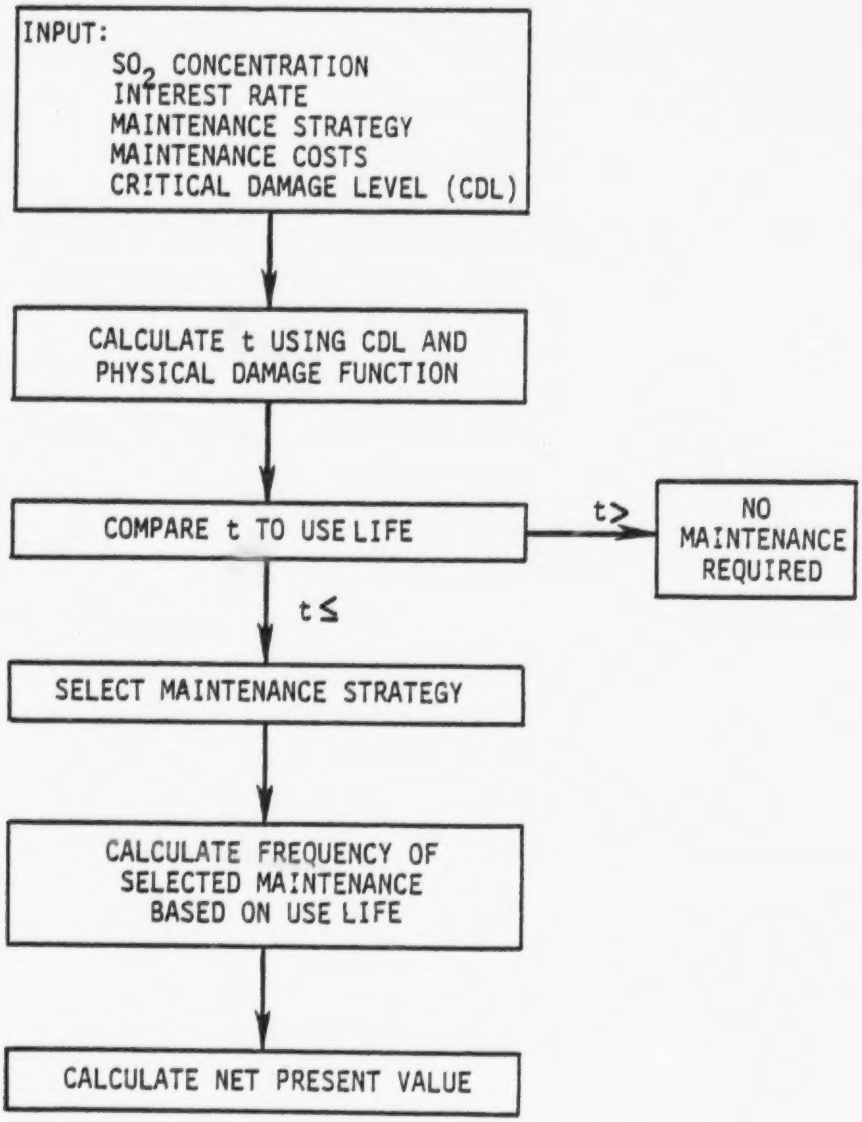
INPUT:
SO2 CONCENTRATION
INTEREST RATE
MAINTENANCE STRATEGY
MAINTENANCE COSTS
CRITICAL DAMAGE LEVEL (CDL)
CALCULATE t USING CDL AND PHYSICAL DAMAGE FUNCTION
COMPARE t TO USE LIFE
t>
NO MAINTENANCE REQUIRED
t≤
SELECT MAINTENANCE STRATEGY
CALCULATE FREQUENCY OF SELECTED MAINTENANCE BASED ON USE LIFE
CALCULATE NET PRESENT VALUE

Figure 5. Least cost model for painting residential wooden structures.

The least cost model for bridges is based on a typical bridge, either long or short. The amount of structural steel, 3.86×10^6 m^2, used to determine the total costs for each maintenance strategy is taken from Table 9. The results of the net present value analysis are presented in Table 25.

Table 25(a) presents the model results for painted steel plate. As with the least cost model for galvanized steel, a use life is defined as 75 years. The NPV is calculated at three interest rates. The results for long bridges and short bridges are presented in Table 25(b) and Table 25(c), respectively. Note that the NPV costs do not represent the actual costs experienced in the Boston area, but indicate an evaluation of the various maintenance strategies.

Least Cost Model for Painted Wooden Surfaces

For painted wood surfaces, a least cost model was developed incorporating the penalty functions presented in Table 14 as well as a no maintenance strategy. Wooden substrates were stressed due to their wide use in residential and older commercial construction and, unlike asphalt shingles, concrete, or brick, the wood tends to decay, progressively increasing repair and maintenance costs.

The model for painted surfaces follows the same methodology for the least cost model as defined in Section 6. A critical damage level of 16 µm of paint loss for the Boston area, was defined using an annual average SO_2 value of 40 $\mu g/m^3$ and the physical damage function (Equation 16). This critical damage level was used as an absolute value of the amount of damage.

TABLE 25A. LEAST COST (1981,$) MODEL RESULTS FOR PAINTED STEEL BUILDING MATERIALS IN THE BOSTON METROPOLITAN AREA USING FOUR MAINTENANCE STRATEGIES OF PAINT (1) AT INITIAL RUST, (2) AT 50% RUST, (3) AT 100% RUST, AND (4) NO MAINTENANCE.

```
MATERIAL:  STEEL - PLATE
MAINTENANCE STRATEGY:  1                                          NPV ($K)
                                      MAINTENANCE
  SO2 LEVEL   USE LIFE        T    ACTIVITIES  5%          10%          15%

     0.0         75.0        25.2           2   83349.0    21758.2      6695.2
    20.0         75.0        23.8           3   97603.3    25475.9      8235.6
    40.0         75.0        22.5           3  106301.0    29188.1      9913.3
    45.0         75.0        22.2           3  108464.0    30138.4     10354.0
    50.0         75.0        21.9           3  110622.0    31097.0     10802.8
    60.0         75.0        21.4           3  114921.0    33037.9     11724.5
    80.0         75.0        20.3           3  123441.0    37007.4     13659.6
   100.0         75.0        19.4           3  131845.0    41080.2     15709.4

MATERIAL:  STEEL - PLATE
MAINTENANCE STRATEGY:  2                                          NPV ($K)
                                      MAINTENANCE
  SO2 LEVEL   USE LIFE        T    ACTIVITIES  5%          10%          15%

     0.0         75.0        31.5           2   86412.4    17224.8      4090.8
    20.0         75.0        29.7           2   95789.4    20597.0      5267.5
    40.0         75.0        28.1           2  105122.0    24192.9      6606.6
    45.0         75.0        27.8           2  107443.0    25123.9      6966.3
    50.0         75.0        27.4           2  109759.0    26067.1      7335.8
    60.0         75.0        26.7           2  114372.0    27988.1      8103.9
    80.0         75.0        25.4           2  123512.0    31959.8      9753.6
   100.0         75.0        24.3           3  142037.0    36408.6     11561.5

MATERIAL:  STEEL - PLATE
MAINTENANCE STRATEGY:  3                                          NPV ($K)
                                      MAINTENANCE
  SO2 LEVEL   USE LIFE        T    ACTIVITIES  5%          10%          15%

     0.0         75.0        37.8           1   78445.6    13497.5      2511.4
    20.0         75.0        35.7           2  102350.0    17105.1      3410.7
    40.0         75.0        33.8           2  113996.0    20656.5      4464.8
    45.0         75.0        33.3           2  116920.0    21590.3      4758.9
    50.0         75.0        32.9           2  119847.0    22541.9      5055.8
    60.0         75.0        32.1           2  125709.0    24496.8      5689.7
    80.0         75.0        30.5           2  137437.0    28603.7      7086.4
   100.0         75.0        29.1           2  149139.0    32955.3      8653.7

MATERIAL:  STEEL - PLATE
MAINTENANCE STRATEGY:  4                                          NPV ($K)
                                      MAINTENANCE
  SO2 LEVEL   USE LIFE        T    ACTIVITIES  5%          10%          15%

     0.0         75.0        42.8           1   76847.9    10480.8      1561.8
    20.0         75.0        40.8           1   84664.7    12664.2      2061.3
    40.0         75.0        39.0           1   92503.3    15055.6      2656.4
    45.0         75.0        38.6           1   94464.3    15685.4      2820.9
    50.0         75.0        38.2           1   96425.2    16327.8      2991.9
    60.0         75.0        37.4           2  116561.0    18151.6      3372.0
    80.0         75.0        35.8           2  127026.0    21114.7      4187.6
   100.0         75.0        34.4           2  137659.0    24308.5      5120.9
```

TABLE 25B. LEAST COST (1981,$) MODEL RESULTS FOR PAINTED STEEL BRIDGES (SMALL) IN THE BOSTON METROPOLITAN AREA USING FOUR MAINTENANCE STRATEGIES OF PAINT (1) AT INITIAL RUST, (2) AT 50% RUST, (3) AT 100% RUST, AND (4) NO MAINTENANCE.

```
BRIDGE SIZE : SMALL

MATERIAL:  STEEL - BRIDGE
MAINTENANCE STRATEGY:  1                                  NPV ($K)
                                   MAINTENANCE
  SO2 LEVEL   USE LIFE         T   ACTIVITIES  5%         10%        15%

       0.0      75.0         6.7       11       20.0        8.9        5.1
      20.0      75.0         6.3       11       21.3        9.6        5.6
      40.0      75.0         6.0       12       22.8       10.3        6.1
      45.0      75.0         5.9       12       23.1       10.5        6.2
      50.0      75.0         5.8       12       23.4       10.7        6.3
      60.0      75.0         5.7       13       24.3       11.1        6.6
      80.0      75.0         5.4       13       25.6       11.8        7.1
     100.0      75.0         5.2       14       27.0       12.5        7.5

MATERIAL:  STEEL - BRIDGE
MAINTENANCE STRATEGY:  2                                  NPV ($K)
                                   MAINTENANCE
  SO2 LEVEL   USE LIFE         T   ACTIVITIES  5%         10%        15%

       0.0      75.0        28.0        2        4.3        1.0        0.3
      20.0      75.0        26.1        2        4.8        1.2        0.4
      40.0      75.0        24.3        3        5.8        1.5        0.5
      45.0      75.0        23.9        3        5.9        1.5        0.5
      50.0      75.0        23.5        3        6.1        1.6        0.5
      60.0      75.0        22.7        3        6.4        1.8        0.6
      80.0      75.0        21.2        3        7.1        2.1        0.7
     100.0      75.0        19.8        3        7.8        2.4        0.9

MATERIAL:  STEEL - BRIDGE
MAINTENANCE STRATEGY:  3                                  NPV ($K)
                                   MAINTENANCE
  SO2 LEVEL   USE LIFE         T   ACTIVITIES  5%         10%        15%

       0.0      75.0        28.7        2        5.5        1.2        0.3
      20.0      75.0        26.8        2        6.2        1.5        0.4
      40.0      75.0        25.0        3        7.4        1.8        0.6
      45.0      75.0        24.5        3        7.6        1.9        0.6
      50.0      75.0        24.1        3        7.8        2.0        0.6
      60.0      75.0        23.3        3        8.2        2.2        0.7
      80.0      75.0        21.8        3        9.1        2.6        0.9
     100.0      75.0        20.3        3       10.1        3.0        1.1

MATERIAL:  STEEL - BRIDGE
MAINTENANCE STRATEGY:  4                                  NPV ($K)
                                   MAINTENANCE
  SO2 LEVEL   USE LIFE         T   ACTIVITIES  5%         10%        15%

       0.0      75.0        65.1        1       10.4        0.5        0.0
      20.0      75.0        60.3        1       13.0        0.8        0.1
      40.0      75.0        56.3        1       16.0        1.2        0.1
      45.0      75.0        55.3        1       16.9        1.3        0.1
      50.0      75.0        54.3        1       17.7        1.4        0.1
      60.0      75.0        52.4        1       19.4        1.7        0.2
      80.0      75.0        48.7        1       23.2        2.4        0.3
     100.0      75.0        45.4        1       27.3        3.3        0.4
```

TABLE 25C. LEAST COST (1981,$) MODEL RESULTS FOR PAINTED STEEL BRIDGES (LARGE) IN THE BOSTON METROPOLITAN AREA USING FOUR MAINTENANCE STRATEGIES OF PAINT (1) AT INITIAL RUST, (2) AT 50% RUST, (3) AT 100% RUST, AND (4) NO MAINTENANCE.

```
BRIDGE SIZE : LARGE

MATERIAL:  STEEL - BRIDGE
MAINTENANCE STRATEGY:  1
                                                                NPV ($K)
                                              MAINTENANCE
   SO2 LEVEL    USE LIFE          t           ACTIVITIES    5%      10%        15%

       0.0         75.0          6.7              11       212.9      98.5       54.5
      20.0         75.0          6.3              11       226.5     102.2       59.6
      40.0         75.0          6.0              12       242.3     109.9       64.7
      45.0         75.0          5.9              12       245.7     111.9       65.9
      50.0         75.0          5.8              12       249.0     113.8       67.2
      60.0         75.0          5.7              13       258.0     117.7       69.8
      80.0         75.0          5.4              13       271.6     125.4       74.9
     100.0         75.0          5.2              14       287.4     133.2       80.1
MATERIAL:  STEEL - BRIDGE
MAINTENANCE STRATEGY:  2
                                                                NPV ($K)
                                              MAINTENANCE
   SO2 LEVEL    USE LIFE          t           ACTIVITIES    5%      10%        15%

       0.0         75.0         28.0               2        43.2      10.0        2.8
      20.0         75.0         26.1               2        48.4      12.2        3.6
      40.0         75.0         24.3               3        57.6      14.7        4.7
      45.0         75.0         23.9               3        59.2      15.4        5.0
      50.0         75.0         23.5               3        60.9      16.1        5.3
      60.0         75.0         22.7               3        64.2      17.5        5.9
      80.0         75.0         21.2               3        71.1      20.6        7.4
     100.0         75.0         19.8               3        78.3      24.0        9.0
MATERIAL:  STEEL - BRIDGE
MAINTENANCE STRATEGY:  3
                                                                NPV ($K)
                                              MAINTENANCE
   SO2 LEVEL    USE LIFE          t           ACTIVITIES    5%      10%        15%

       0.0         75.0         28.7               2        55.2      12.8        3.3
      20.0         75.0         26.8               2        61.9      15.1        4.4
      40.0         75.0         25.0               3        73.6      18.3        5.7
      45.0         75.0         24.5               3        75.7      19.2        6.0
      50.0         75.0         24.1               3        77.9      20.1        6.4
      60.0         75.0         23.3               3        82.2      21.9        7.2
      80.0         75.0         21.8               3        91.3      25.8        9.0
     100.0         75.0         20.3               3       100.7      30.2       11.1
MATERIAL:  STEEL - BRIDGE
MAINTENANCE STRATEGY:  4
                                                                NPV ($K)
                                              MAINTENANCE
   SO2 LEVEL    USE LIFE          t           ACTIVITIES    5%      10%        15%

       0.0         75.0         65.1               1        41.7       2.0        0.1
      20.0         75.0         60.5               1        52.2       3.1        0.2
      40.0         75.0         56.3               1        64.2       4.7        0.4
      45.0         75.0         55.3               1        67.4       5.2        0.4
      50.0         75.0         54.3               1        70.7       5.7        0.5
      60.0         75.0         52.4               1        77.7       6.8        0.7
      80.0         75.0         48.7               1        92.8       9.6        1.1
```

Several maintenance strategies were defined corresponding to those presented in Table 14, including a no maintenance strategy. The physical damage function was used in conjunction with the critical damage level and varying annual average SO_2 values to predict t, defined as the painting frequency. As previously stated, t is equal to 5 years at current conditions within the Boston Metropolitan Area. A maintenance frequency, identified as t + n, where n is defined as an interger year based on the selected maintenance strategy (Table 14), may then be selected and the costs associated with this strategy over the use life of the structure may be calculated.

The effect of SO_2 on a wooden structure is limited to damage to the protective coating. Once the paint fails to protect, then more serious damage occurs to the wooden substrate but such damage is independent of SO_2 concentration. For example, under current conditions in the Boston area, a painted surface should maintain its protective properties for 5 years. After 7 years of exposure, or t + 2, extensive scraping and sanding with full priming are required. At lower levels of SO_2, the value of t may be larger, perhaps 7 years, therefore extensive scraping and sanding will not be required until the ninth year (t + 2). The emphasis on wooden structures is based on the fact that other substrates, such as shingles, brick and concrete do not suffer similar degradation as wood, at least not over the relatively for short periods of concern.

The flow of the model is presented in Figure 5. Based on the annual average SO_2 value, the physical damage function and critical damage level of 16 μm is used to define a value for t. Under lower annual average SO_2 conditions than those currently experienced in the Boston area, t will be greater than 5 years; at high annual average SO_2 conditions, t will be less than 5 years. This value of t is applied with each maintenance frequency, maintenance costs, the use life and the number of maintenance activities over the use life to produce a net present value cost. The maintenance strategies selected for evaluation of painted wooden surfaces are presented in Table 26.

The results of the modeling analysis are presented in Table 27. At higher interest rates, the least cost maintenance strategy is to perform no maintenance (strategy 7) while at lower interest rate of 5 percent either strategy 1 or strategy 2 should be selected depending upon the SO_2 level. The net present value costs are based on a maintenance cost for each structure rather than a surface area cost. A total cost for the Boston Metropolitan Area may be derived by using a figure of 400,000 structures (CRA 1981). Again, it must be noted that these cost figures should not be directly compared or be considered as precise estimates, but merely as a demonstration of the model.

TABLE 26. MAINTENANCE STRATEGIES FOR PAINTING WOODEN STRUCTURES IN THE BOSTON AREA*

Maintenance Strategy	Elapsed Time	Description	Unit Cost (1981,$)
1	t	Recoated at minimal cost	$ 2,000
2	t + 2	Extensive scraping and sanding, spot priming	2,700
3	t + 4	Extensive scraping and sanding, full priming	3,700
4	t + 5	Sanding to bare wood,	4,500
5	t + 6	Sanding to bare wood, repair rot	5,300
6	t + 7	Sanding to bare wood, replace shingles or boards	6,200
7	t + 35	Replace structure	65,000

*See Table 14.

TABLE 27. LEAST COST (1981,$) MODEL RESULTS FOR A PAINTED WOODEN STRUCTURE IN THE BOSTON METROPOLITAN AREA USING SEVEN MAINTENANCE STRATEGIES.

```
MATERIAL: PAINTED WOOD
MAINTENANCE STRATEGY:  1                                   NPV ($K)
                                  MAINTENANCE
  SO2 LEVEL   USE LIFE        t   ACTIVITIES  5%           10%          15%

       0.0       75.0       8.4        8        3.8         1.6          0.9
      20.0       75.0       7.9        9        4.1         1.8          1.0
      40.0       75.0       7.5        9        4.4         1.9          1.1
      45.0       75.0       7.4       10        4.5         1.9          1.1
      50.0       75.0       7.3       10        4.5         2.0          1.1
      60.0       75.0       7.1       10        4.7         2.1          1.2
      80.0       75.0       6.8       11        5.0         2.2          1.3
     100.0       75.0       6.5       11        5.2         2.3          1.4

MATERIAL: PAINTED WOOD
MAINTENANCE STRATEGY:  2                                   NPV ($K)
                                  MAINTENANCE
  SO2 LEVEL   USE LIFE        t   ACTIVITIES  5%           10%          15%

       0.0       75.0      10.4        7        4.0         1.6          0.8
      20.0       75.0       9.9        7        4.2         1.7          0.9
      40.0       75.0       9.5        7        4.4         1.8          1.0
      45.0       75.0       9.4        7        4.4         1.9          1.0
      50.0       75.0       9.3        8        4.6         1.9          1.0
      60.0       75.0       9.1        8        4.7         1.9          1.0
      80.0       75.0       8.8        8        4.9         2.1          1.1
     100.0       75.0       8.5        8        5.1         2.2          1.2

MATERIAL: PAINTED WOOD
MAINTENANCE STRATEGY:  3                                   NPV ($K)
                                  MAINTENANCE
  SO2 LEVEL   USE LIFE        t   ACTIVITIES  5%           10%          15%

       0.0       75.0      12.4        6        4.3         1.6          0.8
      20.0       75.0      11.9        6        4.5         1.7          0.9
      40.0       75.0      11.5        6        4.7         1.9          0.9
      45.0       75.0      11.4        6        4.8         1.9          0.9
      50.0       75.0      11.3        6        4.8         1.9          1.0
      60.0       75.0      11.1        6        4.9         2.0          1.0
      80.0       75.0      10.8        6        5.1         2.1          1.1
     100.0       75.0      10.5        7        5.4         2.2          1.1

MATERIAL: PAINTED WOOD
MAINTENANCE STRATEGY:  4                                   NPV ($K)
                                  MAINTENANCE
  SO2 LEVEL   USE LIFE        t   ACTIVITIES  5%           10%          15%

       0.0       75.0      13.4        5        4.7         1.7          0.8
      20.0       75.0      12.9        5        4.9         1.8          0.9
      40.0       75.0      12.5        5        5.1         2.0          0.9
      45.0       75.0      12.4        6        5.3         2.0          1.0
      50.0       75.0      12.3        6        5.3         2.0          1.0
      60.0       75.0      12.1        6        5.4         2.1          1.0
      80.0       75.0      11.8        6        5.6         2.2          1.1
     100.0       75.0      11.5        6        5.8         2.3          1.1

MATERIAL: PAINTED WOOD
MAINTENANCE STRATEGY:  5                                   NPV ($K)
                                  MAINTENANCE
  SO2 LEVEL   USE LIFE        t   ACTIVITIES  5%           10%          15%

       0.0       75.0      14.4        5        5.0         1.8          0.8
```

TABLE 27 (CONT.)

20.0	75.0	13.9	5	5.3	1.9	0.9
40.0	75.0	13.5	5	5.5	2.0	0.9
45.0	75.0	13.4	5	5.5	2.0	1.0
50.0	75.0	13.3	5	5.6	2.1	1.0
60.0	75.0	13.1	5	5.7	2.1	1.0
80.0	75.0	12.8	5	5.9	2.2	1.1
100.0	75.0	12.5	6	6.2	2.3	1.1

MATERIAL: PAINTED WOOD
MAINTENANCE STRATEGY: 6

				NPV ($K)		
SO2 LEVEL	USE LIFE	t	MAINTENANCE ACTIVITIES	5%	10%	15%
0.0	75.0	15.4	4	5.3	1.8	0.8
20.0	75.0	14.9	5	5.6	2.0	0.9
40.0	75.0	14.5	5	5.8	2.1	0.9
45.0	75.0	14.4	5	5.9	2.1	1.0
50.0	75.0	14.3	5	6.0	2.1	1.0
60.0	75.0	14.1	5	6.1	2.2	1.0
80.0	75.0	13.8	5	6.2	2.3	1.1
100.0	75.0	13.5	5	6.4	2.4	1.1

MATERIAL: PAINTED WOOD
MAINTENANCE STRATEGY: 7

				NPV ($K)		
SO2 LEVEL	USE LIFE	t	MAINTENANCE ACTIVITIES	5%	10%	15%
0.0	75.0	43.4	1	7.8	1.0	0.2
20.0	75.0	42.9	1	8.0	1.1	0.2
40.0	75.0	42.5	1	8.2	1.1	0.2
45.0	75.0	42.4	1	8.2	1.1	0.2
50.0	75.0	42.3	1	8.2	1.2	0.2
60.0	75.0	42.1	1	8.3	1.2	0.2
80.0	75.0	41.8	1	8.5	1.2	0.2
100.0	75.0	41.5	1	8.6	1.2	0.2

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